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TECHNICAL REPORT
NATICK/TR-99/040

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A HIGHLY DAMPED, HIGH-STRENGTH, PUNCTURE-RESISTANT FABRIC FOR MULTI-THREAT PROTECTIVE UNIFORMS

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Report developed under a Small Business Innovative Research contract. The Phase I project was very successful in demonstrating the feasibility of using a superelastic Nitinol shape memory alloy to improve cut, tear, and puncture resistance of military Battle Dress Uniform (BDU) fabric. The Nitinol reinforcement increased cut-resistance by 20 times and tear resistance by 2.5 times the values for current BDU fabric. Cotton/Nylon plain weave fabrics were fabricated in small lots with excellent quality for testing. Various reinforcements were added to demonstrate enhanced mechanical performance. The force-displacement tensile curves from the Modified Grab Test results show that the addition of Nitinol to the fabric doesn't significantly alter flexibility level. The fabrics experienced a 50 to 60 percent increase in breaking strength over the plain fabric with the 5 and 10 Nitinol fibers per inch. Calculations of areal density do not show significant difference between reinforced fabric and plain fabric. Fabric does not kink unless subjected to very severe loads. Wrinkles cannot develop because the shape memory effect returns the Nitinol reinforcement to original shape. Nitinol provides an electrical conduit in the uniform that minimizes shock and static discharge. The Phase I effort has positively demonstrated the feasibility of gaining improved protection in textiles without sacrificing fabric flexibility.

14. SUBJECT TERMS

PROTECTIVE CLOTHING	MULTI THREAT ENVIRONMENTS		HIGH STRENGTH
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REINFORCED FIBERS	TEAR RESISTANCE	FABRICS	TEXTILES

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Preface

The demonstration and feasibility study for a novel improvement for cut and puncture-resistant protective clothing and uniform fabric is presented in this report. The research was funded by a 1998 Small Business Innovative Research Phase I contract through the Office of the Secretary of Defense and monitored by the U.S. Army Soldier & Biological Chemical Command-Natick under the direction of Ms. Carole Winterhalter. DSM-SAE herein demonstrates the feasibility of using a shape memory alloy to greatly improve protective fabric. The Phase I project was very successful in demonstrating the feasibility of using a superelastic Nitinol shape memory alloy to improve cut, tear, and puncture resistance of military Battle Dress Uniform (BDU) fabric. The Nitinol reinforcement increased cut-resistance by 20 times and tear resistance by 2.5 times the values for current BDU fabric. Cotton/Nylon plain weave fabrics were fabricated in small lots with excellent quality for testing. Various reinforcements were added to demonstrate enhanced mechanical performance. The force-displacement tensile curves from the Modified Grab Test results show that the addition of Nitinol to the fabric doesn't significantly alter flexibility level. The fabrics experienced a 50 to 60 percent increase in breaking strength over the plain fabric with added Nitinol fibers. Calculations of areal density did not show significant difference between reinforced fabric and plain fabric. The reinforced fabric does not kink like other metallic reinforced fabric unless subjected to very severe loads. Wrinkles cannot develop because the shape memory effect returns the Nitinol reinforcement to original shape. Nitinol also provides an electrical conduit in the uniform that minimizes shock and static discharge. The Phase I effort has positively demonstrated the feasibility of gaining improved protection in textiles without sacrificing fabric flexibility.

Executive Project Summary

Results

The Phase I project was very successful in demonstrating the feasibility of using a superelastic shape memory alloy called **Nitinol** to improve cut, tear, and puncture resistance of fabric similar to the military Battle Dress Uniform (BDU) rip-stop fabric. The Nitinol reinforcement increased cut-resistance by 20 times and tear resistance by 2.5 times the standard BDU rip-stop fabric values (Fig. 1). While the puncture resistance was not directly measured, a relative strength in puncture is often calculated by taking a mean between the cutting and tearing (or tensile) response of a material. In this fashion, we may assume that the puncture resistance is roughly 2.5 to 10 times that of standard BDU fabric. The Phase I effort has positively demonstrated the feasibility of gaining improved protection in textiles without sacrificing fabric flexibility.

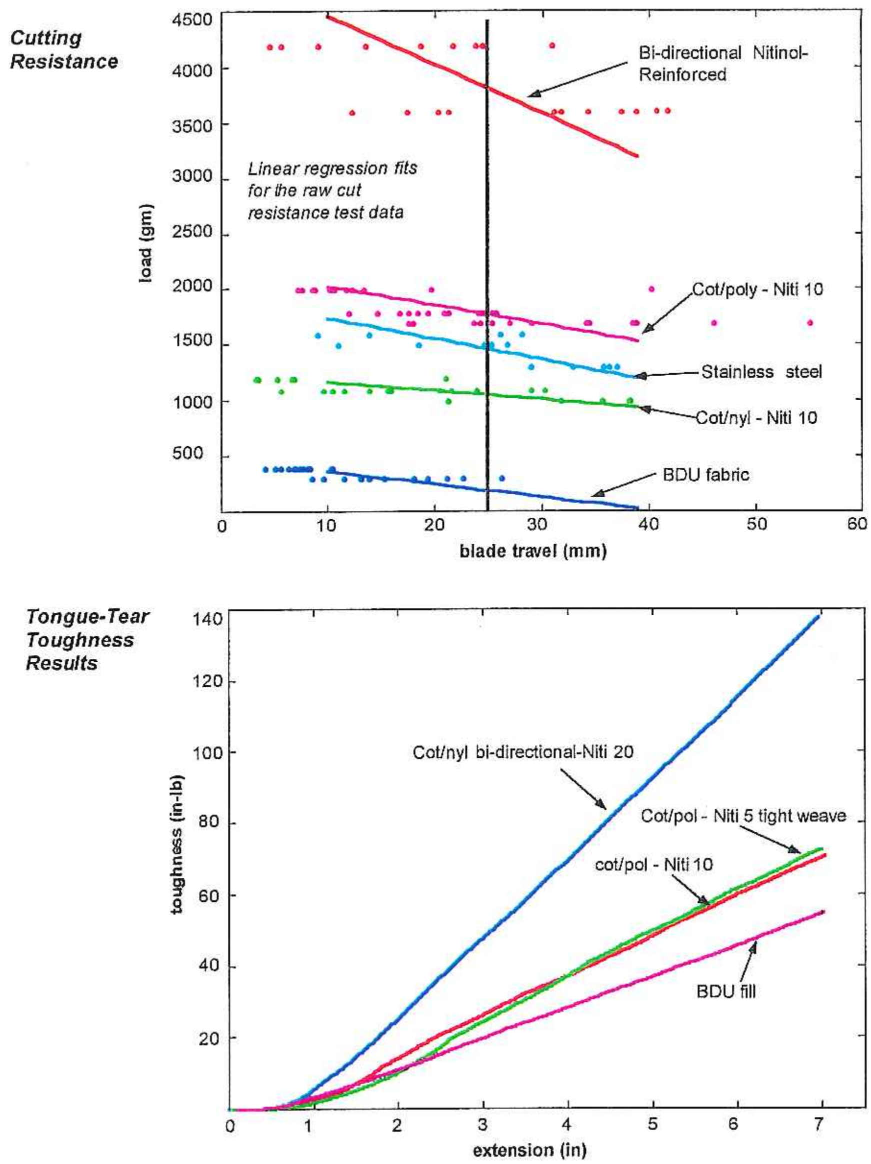


Figure 1. Cut-resistance results (above) and tear results (below) indicate the significant increase in performance of the Nitinol reinforced fabric over the BDU fabric

In this final report for the Phase I project, the results of the testing, fabrication and background study and experiments will be presented. The basis of the superelastic or shape memory effect in the response of the Nitinol is explained and the method for incorporating the Nitinol into the weave is presented. Discussion of the individual fiber results and fabric performance results are presented, and development directions for Phase II are given.

The Nitinol fibers (nickel-titanium shape memory alloy) are a highly flexible and extremely strong, superelastic mono-filament reinforcement for the clothing. The protective clothing fabrics make use of the extreme elasticity or superelasticity in the metallic Nitinol Shape Memory Alloy fibers. The superelastic effect is a result of the shape memory effect of the Nitinol. Because of the shape memory effect in the Nitinol, the extreme elasticity or superelastic effect enables an increase in cut, puncture and tear resistance without increasing the stiffness of the fabric. This concept is described in detail in Section 1.

The Nitinol fibers are used as reinforcement for fabrics made from cotton/nylon and cotton/poly to give the fabrics increased cut, puncture and tear resistance without decreasing the flexibility or comfort of the fabric. Conventional hard metal fibers such as stainless steel or titanium might also increase the tear resistance, but since the metal is so stiff and inflexible, the resulting fabric is stiff or "boardy" and uncomfortable. Kevlar® or glass reinforcement fibers also tend to be too stiff in stretching compared to the nylon, cotton or polyester host fabrics and cause the fabric to lose its give or stretch-ability.

The increased cutting strength and puncture resistance of the fabric will benefit those in the military and the glass handling, woodcutting, meatpacking, and metalworking industries, among others. High levels of intrinsic damping are also a characteristic of the Nitinol fibers. Integrating this new composite fabric into protective gloves for workers using vibrating equipment is therefore also viewed as having a high potential for commercial development. Additionally, the Nitinol fibers may be integrated in such a fashion that when the fabric is subjected to heavy vibrational loads, the fibers will cycle through Nitinol's two phase transitions, absorbing large amounts of energy. These Nitinol enhanced fabrics will primarily benefit workers in occupations involving heavy wind loads, particularly buffeting loads, such as those experienced on the flight deck of an aircraft carrier.

Task List: The original task list as proposed is provided below as a reference to the reader.
1. Manage Project and Obtain Industrial Partners
2. Identify Target Fabrics for Improvement
3. Evaluate Performance for Cutting and Puncture
4. Evaluate Fabric Damping Properties
5. Model Nitinol Enhanced Fabric Conceptualization
6. Determine Multi-Threat Fabric Compatibility

Modifications to the Task: To satisfy the needs of the U.S. Army Soldier Systems Command at the Natick Research, Development and Engineering Center, the project is focusing on cut, puncture and tear resistance. Work in the area of vibration transmission improvements may be addressed in Phase II after cut, tear and puncture resistance improvements have been demonstrated. Therefore, Task 4 was set aside for the Phase I effort.

Work Completed during the effort:

Months 1 and 2: DSM-SAE completed significant background study and fabric investigations to determine critical parameters for the new fabric. DSM-SAE engineers collected data on standard cotton/nylon fabric from the Army as currently used in BDUs and data on potential materials for protective clothing. Preliminary testing was performed on some Nitinol-reinforced specimens to illuminate important design issues. To develop commercial contacts for fabric development, engineers from DSM-SAE visited the ASTM mid-year conference and committee meetings in Atlanta. They gained valuable insight into current fabric testing procedures.

Months 3 and 4: DSM engineers have formed significant commercial and industrial relationships with manufacturers of the military uniform fabric and producers of protective clothing. The relationship with Mike Kilkenney and Gene Munns of Greenwood Mills has aided DSM in production of the reinforced fabric. They have provided valuable insight into the current fabrication methods, and they gave us samples of the cotton/nylon yarn for use in fabricating samples. DSM-SAE has also formed commercial relationships with Best Manufacturing Co. and Modern Headware, LTD, which are makers of protective gloves and cut-resistant clothing.

Additionally, we have spent a significant portion of the two months identifying sample weavers, setting up for the weaving process, working through the peculiarities of weaving the Nitinol into the fabric, and arranging for the actual production of the fabric. Samples have been produced with two sample weavers using both the BDU host fabric yarn (cotton/nylon) and a similar cotton/polyester blend yarn. We also have the potential for using a host yarn made from other high strength fibers with Nitinol reinforcement. In the coming weeks, DSM engineers will be in the process of testing samples and evaluating their response.

Months 5 and 6: The project was completed in early November 1998. Testing of the fabric was started in mid-September and continued through October 1998. A number of samples were fabricated and tested. Various densities of Nitinol reinforcement and various diameters and forms were investigated. The two months were very busy with testing at both Florida State University and Best Manufacturing and visiting with fabricators on a daily basis. The final report will present the testing results and final evaluation data.

Costs of Contract: In percentages, the amount of money spent in the six months of the contract as compared to the budgeted levels are:

98% - Direct labor
103% - Fabrication, raw materials, supplies, and testing costs
100% - Labor Overhead
100% - G&A Costs

All of the budgeted costs for the contract were used for the contract completion. Costs met original budget guidelines within 3% of the initial values.

1. Introduction to the Innovation

1.1. Cut Resistance of Nitinol-SMA

In the field of protective clothing, many different materials are used to provide cut, tear and puncture resistance. The key for yarns or fiber additions to provide each of the required performances is the following:

For Cut Resistance:

-High strength fibers with high levels of surface hardness are better than soft high-strength fibers.
-A few large-diameter fibers or filaments give better results than many smaller-diameter filaments.
-The ability to deform under the cutting blade is important.

For Tear Resistance:

-High strength and high elongation is important.
-High tensile strength and the ability to bunch up with neighboring fibers are important.
-Many high-strength, highly twisted filaments in a yarn give greater tensile and cut strength.
-More loosely packed fabric can be an advantage for tear resistance.

For Puncture Resistance

-High levels of hardness and shear resistance (ultimate tensile strength) are important.
-A high single-fiber modulus is important under high-speed puncture.
-The same requirements for cut and tear resistance.

Superelastic Nitinol-SMA fits the requirements for many of these specifications better than most materials. It also has the ability to be compatible with textile processes and flexibility requirements for clothing. Within the field of protective clothing, a wide range of materials and fabrics are used for various applications. Conventional fabrics containing high-strength organic fibers such as Kevlar®/aramid, nylon, UHMW polyethylene, and polypropylene do not have the innate cut resistance or high elasticity of superelastic Nitinol. Figure 2 shows the shear cutting resistance of superelastic Nitinol compared to other composites and metals from Paine (1994).

In the current Phase I study, Nitinol was briefly compared to Kevlar® and stainless steel reinforcements. Both Kevlar® and stainless steel are substantially stiffer than Nitinol in stretching. They also under-performed the Nitinol in cut resistance. When used in protective clothing, organic fibers may perform adequately when loaded in tension by rotating or jagged cutters. In applications where protection from cutting or puncture is the requirement, fabrics made from these fibers perform less adequately, however, because of their lower strength in the transverse directions and open-pore woven nature. Cutting by a narrow blade tends to load a small area of the fabric in compression normal to the axial direction of the fibers, and puncture tends to simply part the fibers. The fibers are cut when the combined state of compression and shear in the material from the blade pressure is greater than the material's transverse compression or shear strength. Metallic fibers are sometimes added to the organic fiber fabrics to increase the cutting protection and puncture resistance of the protective clothing.

Using superelastic Nitinol fibers as additives to the organic fiber fabrics instead of conventional metallic fibers increased the fabric's cutting and puncture resistance and eliminated the

disadvantages associated with the conventional metallic fiber additives. The transverse strength and toughness of the fibers proved to be as high as high-strength steels, so they increased the cutting resistance. The fibers are readily formed into a mesh during Phase II to enhance the puncture resistance. The fatigue resistance of the fibers is high because they can be strained or flexed to great levels without undergoing permanent phase change, unlike conventional metals.

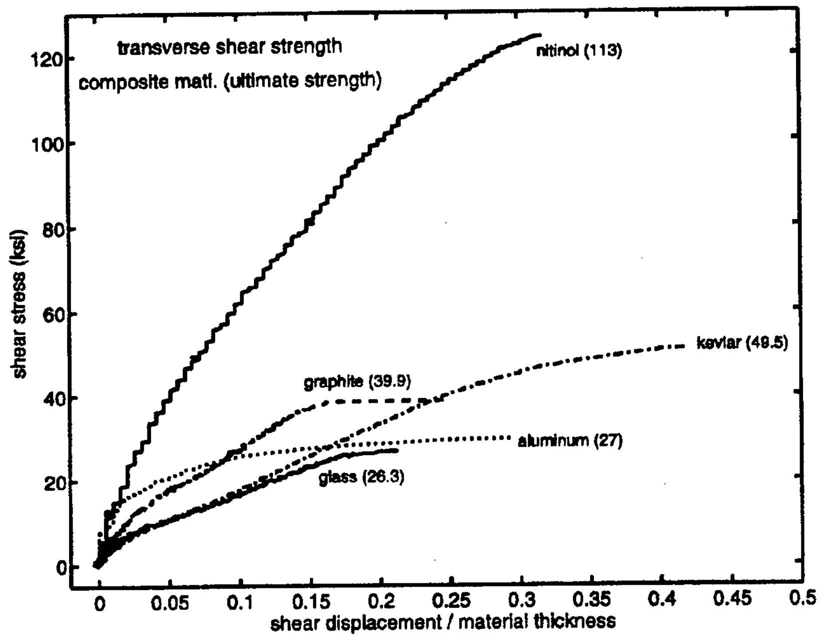


Figure 2. Cutting shear strength of superelastic Nitinol versus various metals and composites. Displacement is normalized by thickness.

1.2. Shape Memory Alloys vs. Conventional Metals – Strain Recovery (Elasticity) and Stiffness

Nitinol, a shape memory alloy of Nickel and Titanium, developed in the Naval Ordinance Laboratory (NOL) in the early 1960s, demonstrates significant shape memory effect. When practical shape memory alloys are considered, Nitinol is by far the superior performer in terms of elasticity and recovery level. The term "shape memory effect" came about because of the material's ability to recover quickly and forcibly from a large amount of stretching or deformation. Most metals can recover from stretching or deformation up to about 1% maximum strain. Nitinol shape memory alloys may recover fully from up to 10% strain. The ability of an SMA to be stretched and then fully recover comes through their unique mechanism of material-yielding during stretching or deformation.

When conventional metals are stretched beyond their elastic limit of 0.5 to 1% strain, they yield through dislocation movement in the material. Dislocation movement results in a permanent set or change in the metal's shape. Therefore, when steel and aluminum are stretched too far, they become permanently distorted. The SMA undergoes a phase transformation as it is deformed or stretched as shown in Figure 3 below. The phases are called Austenite (high temperature phase) and martensite (low temperature phase). Within the molecular bond structure of the Nitinol metal, a twinning appears (see "B" in Fig. 3) as it cools below its Austenite state (see "A" in Fig. 3). The twinning possesses right angles ("B") which unfold in a simple shearing motion when the material is re-heated to its Austenite temperature ("A"). When the material is deformed up to

10% without being heated ("C"), the strain causes a shearing motion whereby the twins flip their orientation to the opposite tilt (detwinning) and stay there until heated above the Austenite temperature ("A"). The crystal lattice untilts with the increase in heat energy and returns to its original shape.

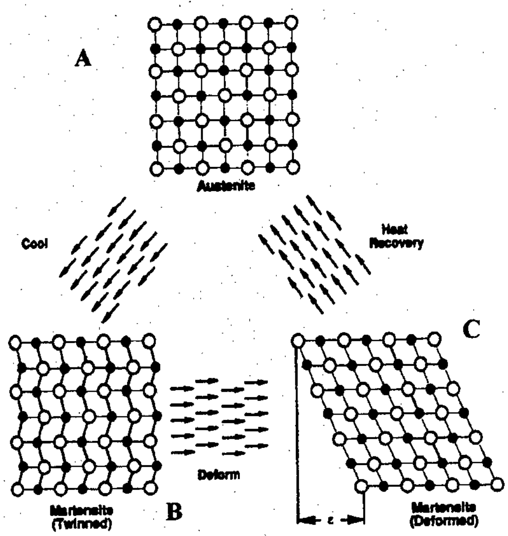


Figure 3. Representation of the Changes in Molecular Bond Structure during Phase Changes in SMA (Hodgson, 1988)

Shape memory alloys that are tuned so that their Austenite temperature is **above** operating temperature can be used as actuators or solid-state linear motors in mechanical systems. Heating the Nitinol-SMA by simply applying a voltage causes them to self-heat and will produce a desired range of motion. Applications for shape memory alloy actuators or motors in uniform systems might include adaptive uniform shape control, selective tensioning or ribbing, and gap sealing around leg or arm holes. Figure 4 gives a representation of the shape memory effect used in linear motors or actuators.

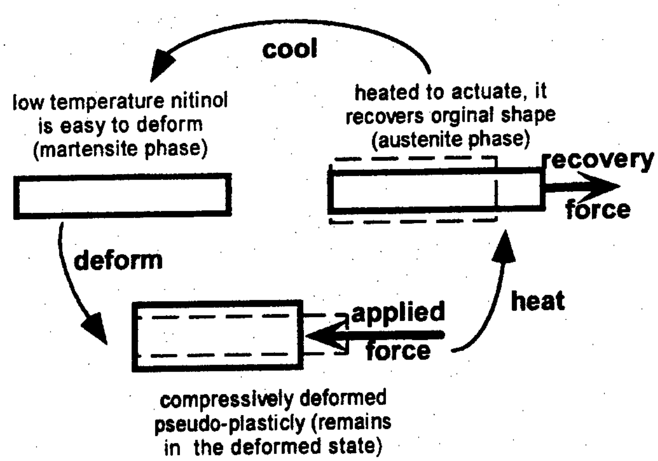


Figure 4. Nitinol - Shape Memory Alloy response for use in linear motors or actuators

1.3. Superelastic vs. Shape Memory Properties of Nitinol

In its superelastic state, Nitinol is used for the BDU fabric reinforcement. The term "superelasticity" arises because the material can effectively be stretched up to 10% and completely recover the stretch like an elastic band. Nitinol attains its superelastic state when the Austenite transition or activation temperature is tuned to be below the operating temperature. With the activation temperature below operating temperature, the normal environment provides enough heat to cause the shape recovery event to occur any time there is a large deformation. The shape recovery becomes an automatic and instantaneous response instead of a delayed or activated response.

Superelasticity is also sometimes termed "mechanical shape memory." The Nitinol transforms upon being stressed. Removal of the stress enables the temperature-induced re-transformation, and the original Nitinol shape is restored. The mechanical benefits of the mechanical shape memory or superelasticity are illustrated in Fig. 5. A superelastic stress-strain curve for a Nitinol spring, compared to that for a typical spring material, piano wire, is shown in Figure 5. For the SMA, the strain is completely recovered. For the piano wire spring, permanent deformation occurs and only a part of the strain is recovered. Using both in fabric would mean that the Nitinol-SMA would remain completely flexible, while the spring steel would be inflexible and plastic-like.

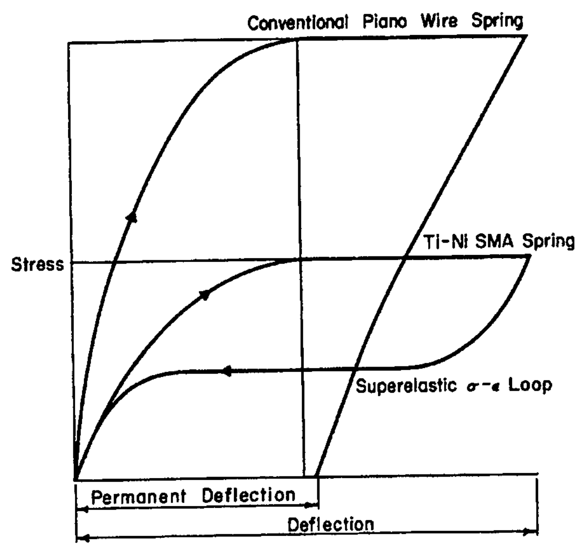


Figure 5. Comparison of springs made of superelastic Nitinol and conventional piano wire

In Fig. 6, various uses for shape memory alloys in uniform systems are presented. The Phase I effort has only focused on the initial region, superelastic Nitinol used for cut, tear and puncture resistance. It should be noted that when superelastic Nitinol is used below –40 degrees C, it still provides superior cut, puncture and tear resistance. However, the Nitinol will not have the ability to immediately spring back to its original shape when flexed. The fabric will therefore be somewhat boardy or stiff, much like some nylons and elastomers.

Using SMA Materials for Reinforcing Uniforms and Soldier Systems

The shape memory effect can be tailored to occur at various temperatures.

-40 to -10 degrees C: *In superelastic state, Nitinol can be used for passive cut and puncture resistance.*

-10 to 40 degrees C: *Nitinol transitions between activated and un-activated state to signal change in soldier's conditions or environment.*

40 to 60 degrees C: *Nitinol can be used as an activated component of the uniform to signal a warning, change uniform properties (shape, etc.) and further aid soldier in performing mission.*

Figure 6. Possible Applications for Shape Memory Alloy in Military Uniform systems

2. Evaluation Results for Phase I Protective Fabrics

The Phase I fabrics were tested in a comprehensive experimental program whereby the Nitinol-reinforced fabric was compared to its own baseline un-reinforced fabric and to the baseline BDU rip-stop fabric. The Phase I sample fabrics were produced by DSM-SAE and by our contracted weavers. Carole Winterhalter of U.S. Army Natick supplied the BDU rip-stop fabric, which is produced by Greenwood Mills. DSM-SAE engineers at DSM-SAE offices, Florida State University and Best Manufacturing Labs performed all testing. First, the military specifications are given, then the mechanical test results.

The tested fabrics with the accompanying designations for clarity in the graph legends:

BDU Fabric (Rip-stop) - BDU
Baseline military fabric of plain weave cotton/nylon

Cotton/Nylon plain-weave – Cot/Nyl-p
Baseline cotton/nylon fabric to imitate the BDU rip-stop material without the periodic doubling of the warp and fill yarns that provides the ripstop effect.

Cot/Nyl 5-Niti/in. (0.003") - Cot/Nyl-5
Baseline cotton/nylon plain weave with 5 Nitinol fibers per inch at 0.003" diameter to add cut-resistance.

Cot/Nyl 10-Niti/in. (0.003") - Cot/Nyl-10
Baseline cotton/nylon plain weave with 10 Nitinol fibers per inch at 0.003" diameter to add improved cut-resistance.

Cot/Nyl 20-Niti/in. (0.005") Twill - Cot/Nyl-20
A cotton/nylon twill weave with 20 Nitinol fibers per inch at 0.005" diameter to add improved cut-resistance, tear strength and grab strength.

Cot/Poly Plain-weave - Cot/Pol-p
Baseline cotton/polyester fabric to imitate BDU rip-stop material without the periodic doubling of the warp and fill yarns that provides the ripstop effect. This material was used because of the initial difficulty in obtaining cotton/nylon yarn.

Cot/Poly 5-Niti/in. (0.005") - Cot/Pol-5
Baseline cotton/poly plain weave with 5 Nitinol fibers per inch at 0.005" diameter to add cut-resistance and tear strength.

Cot/Poly 10-Niti/in. (0.005") - Cot/Pol-10
Baseline cotton/poly plain weave with 10 Nitinol fibers per inch at 0.005" diameter to add cut-resistance and tear strength.

Cot/Nyl-Kevlar® (0.002") - Cot/Pol-K
Baseline cotton/nylon plain weave with 10 Kevlar® 29 yarns per inch at 0.002" diameter to try to add cut-resistance. (Only tested in cut resistance)

Stainless Steel Screen - Stainless-Steel
A sample piece of fine stainless steel screen was tested in cut resistance only because of the high toughness of stainless steel. The Grab and Tongue Tear Tests were not performed, as the material is not considered a fabric.

The Mechanical Tests that were performed on the various fabrics include the following:

Cut-Resistance Test - section 2.2
Tongue Tear Test - section 2.3
Grab Test - section 2.4
Density Test - section 2.5

2.1. Standard Specifications for Rip-stop BDU fabric performance

A summary of the Military Specifications that DSM-SAE aimed to achieve in addition to an increase in cut-tear-puncture resistance is given below as obtained from Military Spec: MIL-C-44436 (GL).

ASTM standards for testing:
D 1424 – Tear Resistance of woven fabrics by Falling Pendulum
D 5034 – Breaking Force and Elongation of Textile Fabrics (Grab Test)

Physical Requirements

Characteristic	Classes 1,2 and 4	Class 4
Weight or Areal Density, (oz./yd^2) Min Max	 6.0 7.0	 6.0 7.0
Yarns per inch, (min) Warp Filling	 104 104	 52 52
Breaking Strength, (lbs.) min Warp Filling	 200 90	 200 90
Tearing Strength Warp Filling	 7 5	 7 5

Weave: The weave will be a plain weave with reinforcement ribs in both the warp and filling directions, forming a uniform pattern. The ribs shall be formed by having every 24th warp end contain two ends of weaving as one and every thirteenth filling contain two picks of weaving as one. Method of testing: visual.

Width: The width of finished cloth will be the minimum acceptable width inclusive of the selvage when fly shuttle looms or shuttleless looms are used with tuck-in selvage looms.

Resistance to Organic Liquid Test.

Dimensional stability: The shrinkage or elongation both in the warp and filling of the finished cloth shall not be greater than 3.5 % for the individual sample unit and not greater than 3% for the lot average when tested as specified.

2.2. Fabric Performance for the Cut-Resistance Test

No military standard currently exists for the cut resistance of BDU fabric, rip-stop or otherwise. Therefore, the ASTM F1790 standard for cut-resistance was followed using an ASTM recommended machine at the Best Manufacturing Labs in Menlo, GA. Fabric is cut with an increasingly higher load on the blade until the blade goes through after 1 inch or 25 mm of travel. When penetration of the sample occurs, the tester automatically stops. Raw data for the length of the stroke versus cut force are fit with a linear regression curve which enables the pinpointing of the data at 25 mm. Cut-resistance test results are shown in Figures 7 and 8.

Cut-Resistance Definition: The cut-resistance is the amount of blade force required to cut though the test fabric at 25 mm of razor blade travel. The blade force is reported as grams of load on the blade.

The sample baseline fabrics and Kevlar® reinforced fabric are shown in Figure 7. It is clear that all of the materials perform similarly. The BDU fabric was tested in both the fill and warp directions to determine if a difference existed. While the red and blue lines in Figure 7 are different, the relative variation is probably due to the difference in weave tightness or fiber packing and number of yarns between the warp and fill directions. The samples produced by DSM-SAE from plain weave cotton/nylon (cot/nyl-p), plain weave cotton/poly (cot/pol-p), and cotton/nylon reinforced with Kevlar® (cot/nyl-k) all fall within 13% of each other – essentially the same response. It was interesting to confirm that Kevlar® does not particularly improve the true cutting resistance.

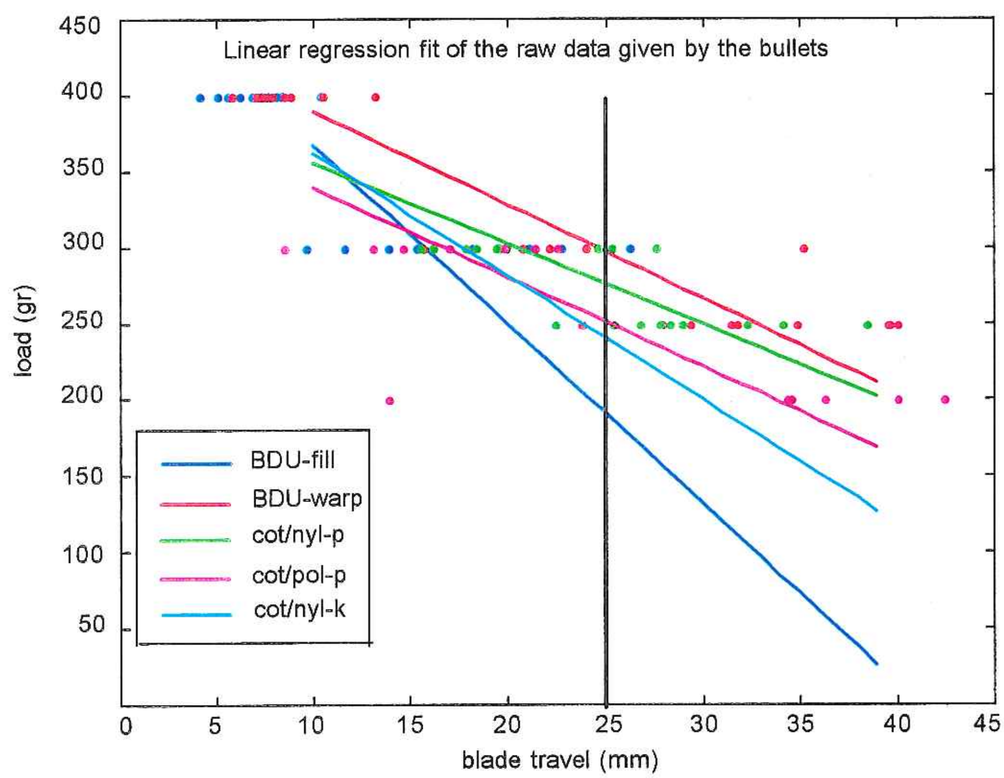


Figure 7. Cut-resistance test results for baseline fabrics and Kevlar® reinforced fabric

For the reinforced fabrics, the cut-resistance is significantly enhanced. The Nitinol-reinforced fabric demonstrates a multiplication of the cut-resistance load depending on the amount and diameter of the Nitinol reinforcement. Figure 8 shows the cut-resistance data.

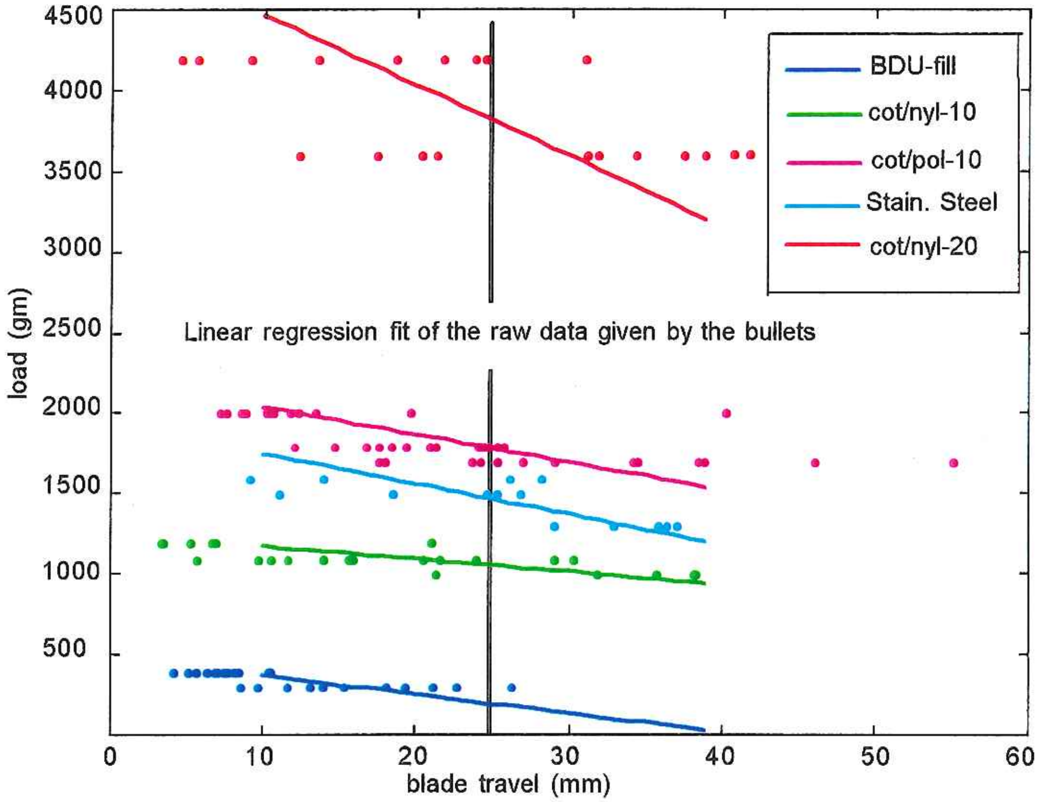


Figure 8. Cut-Resistance test results for selected fabrics

Figure 8 indicates very high cut-resistance for the bi-directional reinforced cotton/nylon fabric with 20 fibers or 0.005" diameter Nitinol per inch (cot/nyl-20). The fact that the Nitinol is bi-directional in the fabric does not particularly help the cut-resistance, since the fabric is tested in either the fill or warp direction, not on the bias. Other observations from Figure 8:

- The cot/nyl-20 is 14 times more cut-resistant than the base cotton/nylon fabric (cot/nyl-p) and 13 to 20 times greater than the BDU. The cut-resistance of the cot/nyl-20 is significant enough to warrant its use in clothing made especially for cut-resistance.
- The cotton/poly with 10 strands of 0.005" Nitinol is 1.7 times as cut-resistant as cotton/nylon with 10 strands of 0.003" Nitinol, indicating the importance of the larger diameter Nitinol fibers to increase cut-resistance.
- The cot/nyl-10 and cot/pol-10 are 5.5 and 9.3 times more cut-resistant than the BDU fill respectively.
- The stainless steel screen was 7.65 times more cut-resistant than the BDU fill. However, it had very low tear toughness, indicating the necessity of fiber bunching and large diameter fibers for achieving tear resistance.
- Even greater cut-resistance can most likely be obtained using Nitinol reinforcement in other types of weave structures.

It will be shown later that while the 0.003" diameter Nitinol resists cutting, as indicated in Figure 8, it is actually weaker than the finished cotton/nylon yarn in the Tear and Grab tests. This is a testament to the high cut resistance of the Nitinol alone. The cut-resistance test data values are shown in bar graph form in Figure 9 and in Table 1 below.

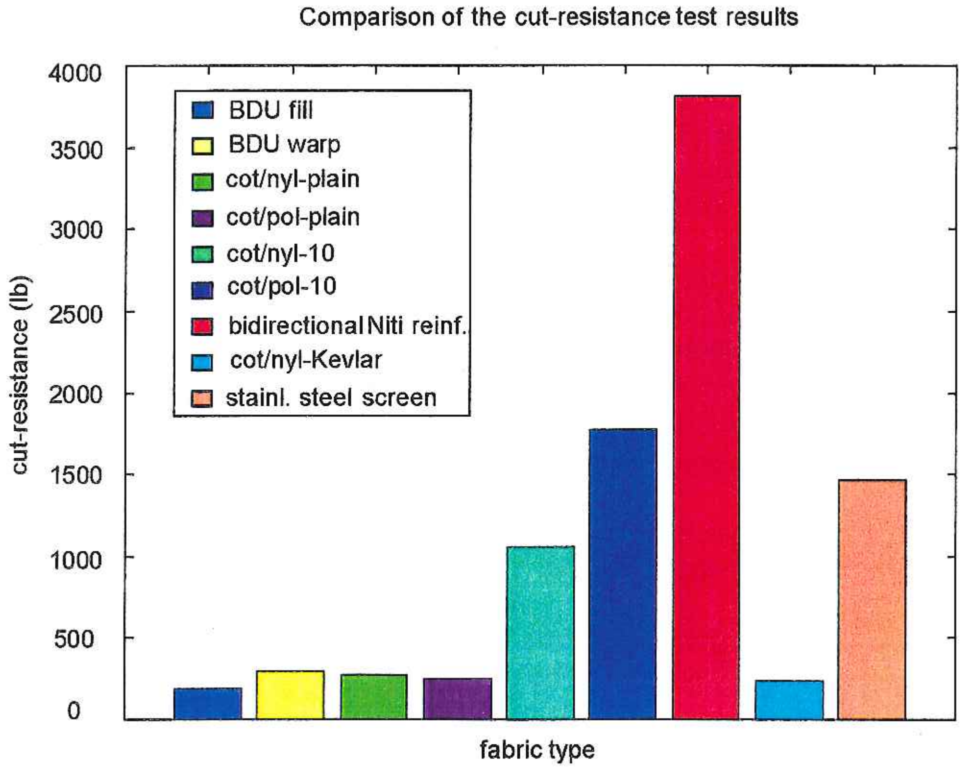


Figure 9. Cut-resistance results comparison chart

Table 1. Cut-resistance data for all of the tested fabrics

Specimens	Cut through load (gm)
BDU fill	190.8
BDU warp	297.1
Cot/Nyl **P**	275.5
Cotton/Pol-P	250.9
Cot/Nyl with Niti-10.(0.003")	1049.7
Cot/Pol with Niti-10. (0.005")	1776.3
Bi-directional cot/nyl with Niti-20	3808.3
Cot/Nyl with *Kevlar®	240.4
Stainless steel screen	1462.1

These results demonstrate the feasibility of using the superelastic Nitinol-SMA as an added reinforcement to the cotton/nylon plain weave to improve cut-resistance. The Phase II effort is warranted by this data.

2.3. Fabric Tearing Strength in the Tongue Tear Test

The military standard for tear resistance uses the Elmendorf tester, following ASTM Standard D1424. This standard yields a single value for the amount of tearing load needed to advance a tear but yields no data about the way the tear progresses or why. The way the tear progresses and the contribution to toughness from the reinforcement are readily observed using the Tongue Tear ASTM standard test, D2261. DSM-SAE chose to use the Tongue Tear method in order to observe the load changing as the tear advanced through the reinforcement. DSM then compared Tongue Tear results from reinforced fabric with results from the baseline BDU and cot/nyl-p fabrics. DSM-SAE assumed that if the fabric performed better than the BDU fabric did, it would satisfy Mil-Specs in terms of tear resistance. Test details are given in Chapter 5.

The Tongue Tear test involves finding the amount of force to advance a tear in the specimen. As the tear advances, each yarn is subjected to progressively increasing tension. Tearing force is recorded as a diagram of increasing and then sharply decreasing spikes as the tear extends. Toughness is a measure of work done on the fabric during tearing, or the area under the load vs. elongation curve. Test results are reported as toughness versus tear elongation. The higher the toughness, the greater the resistance to tearing.

Tongue Tear Definition: Toughness in tear means the average amount of energy (toughness) used to force a tear in the fabric for approximately 3.5 inch of tear or 7 inch of grip extension

The average toughness of the cotton/polyester based fabrics as the tear progresses (extends) through the fabric is given in Figure 10. The cotton/poly with 10-0.005" diameter Nitinol fibers

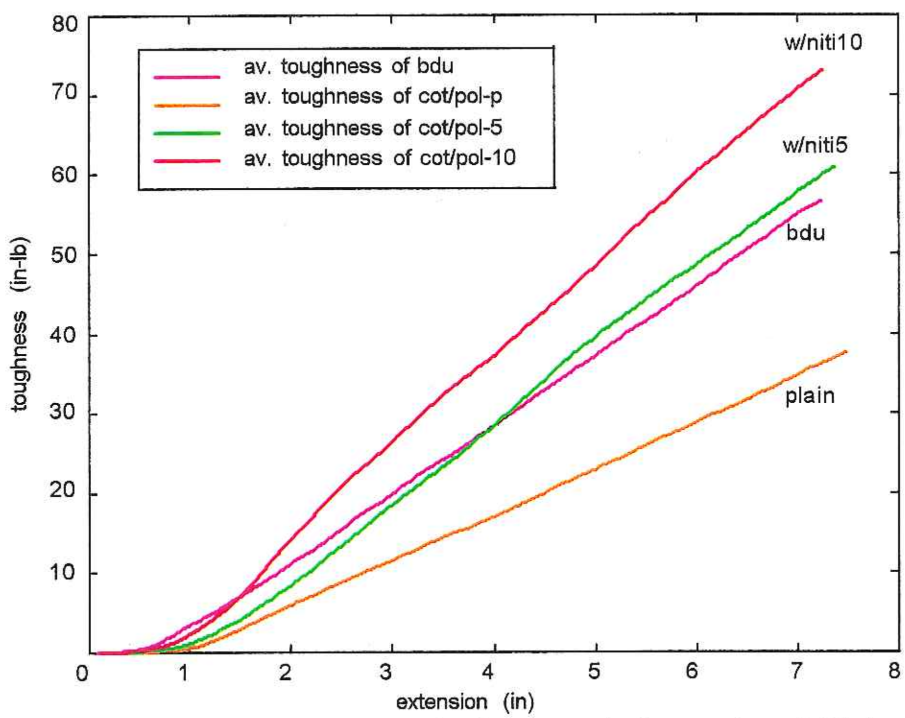


Figure 10. Tongue Tear test results for cotton/polyester-based fabric

per inch had significantly higher toughness than the plain BDU fabric. In Figure 11 the BDU fabric is much tougher than the cot/nyl-p or any of the cot/nyl fabrics with 0.003" diameter Nitinol. This indicates that the weaving techniques used by DSM-SAE may affect the toughness of the imitation BDU fabric. Such effects will be addressed in Phase II.

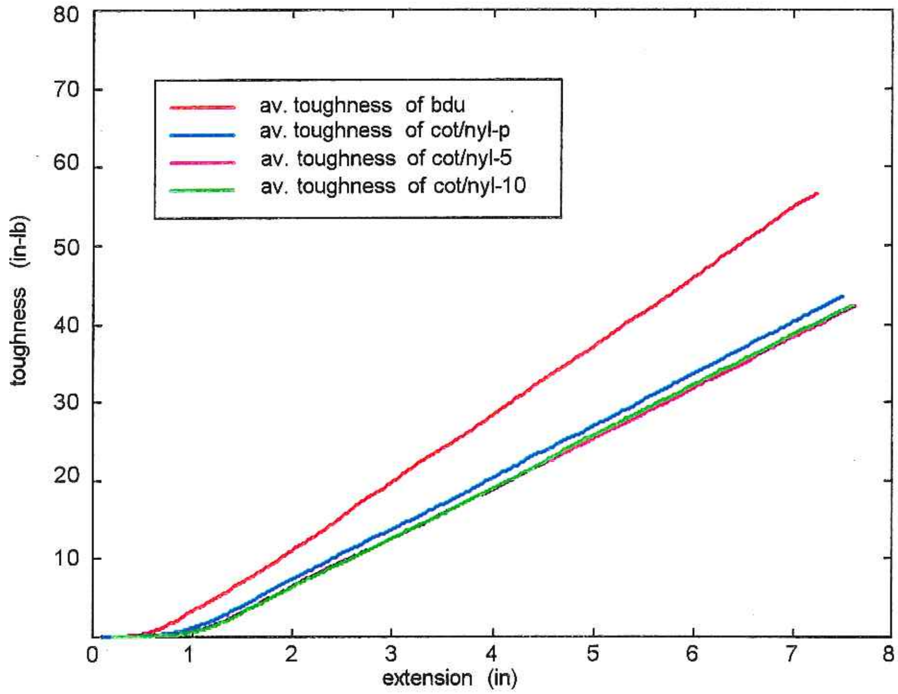


Figure 11. Toughness comparison for cotton/nylon-based fabric with BDU fabric

The test data from for these averages and a sample load vs. extension plot for each of the fabrics is shown in Figure 12 and 13. Observations from Figures 10, 11 and 12 are as follows:

- Nitinol reinforcement at 0.005" (Figure 10) can increase tear resistance by 100% over the plain fabric because the Nitinol is thick enough to aid in resisting the tear.
- The toughness of the BDU fabric is higher than that of cot/pol-plain and cot/nyl-plain, because of the ripstop reinforcement in fill direction and fabrication differences.
- Nitinol reinforcement at 0.003" diameter has no impact on the cot/nyl-p, as shown by the clumped nature of the cot/nyl-p and cot/nyl-5 and -10 toughness curves in Figure 11.
- In tear, the yarns fail individually in tension. The fabric weave quality can have a great influence on tear strength. Fiber strength or toughness is only part of the equation.
- Grouping of the individual yarns resists tear advancement as the tear progresses.
- Nitinol 0.005" can encourage grouping and bridging of the fiber tension load during the tear.
- Pulling out of the Nitinol from the weave during the tearing can increase the amount of energy needed to advance the tear.

Understanding the issues that occur during the tear process is important for improving the fabric. DSM-SAE also looked into a looser weave structure for one sample fabric. Just slight changes in the tightness of the weave (54 yarns per inch instead of 52) can greatly change the tear resistance. The results in Figures 10, 11, and 12 demonstrate the benefit of using 0.005" diameter Nitinol as a tear reinforcement.

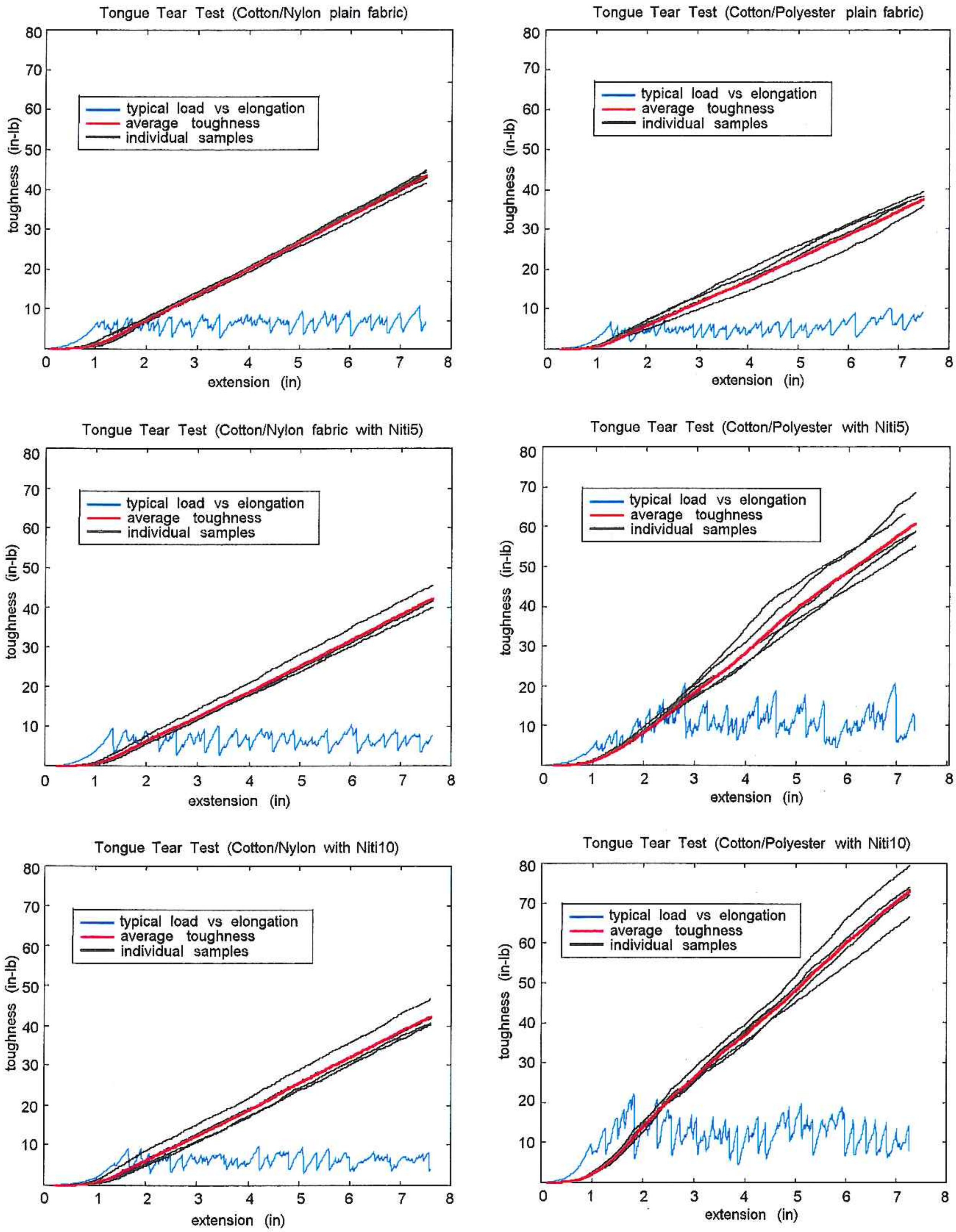
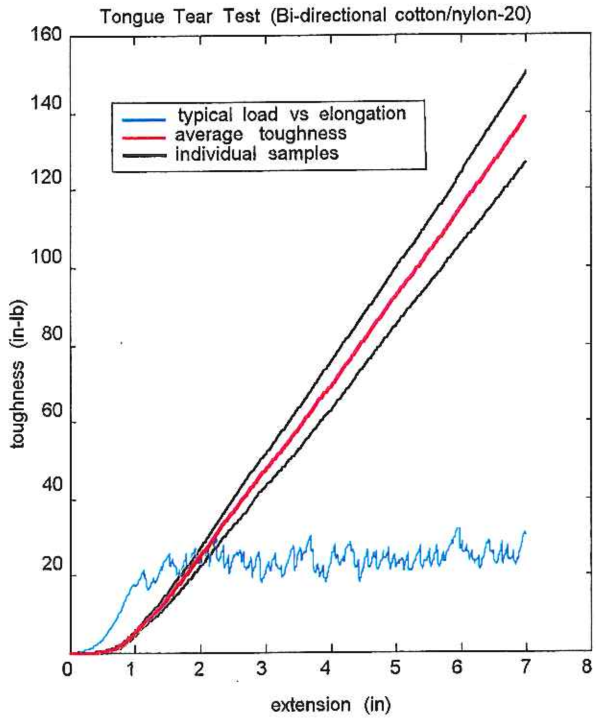


Figure 12. Tongue Tear individual test results. Cot/nyl family with 0.003" Nitinol (left column). Cot/pol family with 0.005" Nitinol (right column). Sample load-extension chart in pounds (blue), toughness for 5 specimens of each type (black), average toughness in red.



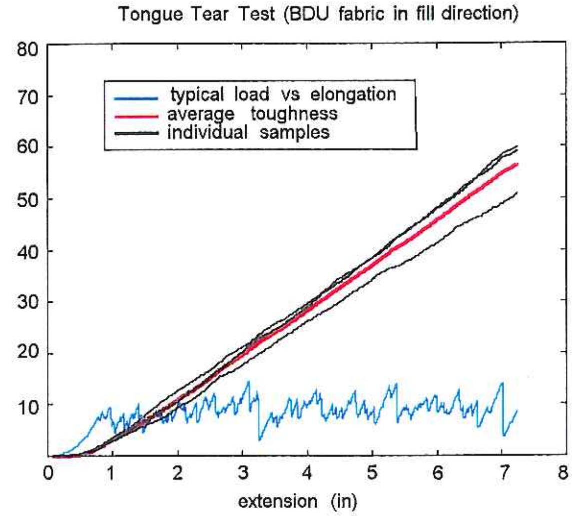


Figure 13. Tongue Tear individual test results. Cot/nyl-20 specimen with 0.005" Nitinol (left). BDU samples (right). Sample load-extension chart in pounds (blue), toughness for 3 specimens of each type (black), average toughness in red.

Results in Figure 13 demonstrate the very significant benefit to tear that 20 pieces of Nitinol 0.005" per inch give to a cotton/nylon twill. As the numbers in Figure 14 and Table 2 below it indicate, Nitinol reinforcement can greatly improve the tear resistance of the BDU fabric. Compared to the baseline cot/pol fabric, the cot/pol-5 and cot/pol-10 caused an increase in toughness by 65% and 200% respectively. The peak force for advancing the tear is improved by an even more significant margin. The bi-directional Nitinol-reinforced cot/nyl was more than 3.5 times the tear toughness of the base cot/nyl and more than 2.6 times the tear strength of the BDU fabric.

Alternate Fabric Considerations

In a final tear test, some cot/pol-5 was woven with a slightly tighter weave. The tongue tear force levels and resulting toughness (see Fig. 14) proved to be significantly greater than the regular cot/pol-5. This illustrates the need for a thorough study in Phase II of the fabrication methods addressing such issues as the weave tightness or weave type and their relationship to fabric performance. The stainless steel screen was also tested in a simple Tongue-Tear procedure. It resulted in only a 0.45 lb. tear force and a 3.2 lb.-in of toughness, a trivial level. Since the stainless steel screen was made up of 0.0012" diameter wires, it is clear that thicker wires benefit the tear resistance as well as cutting resistance.

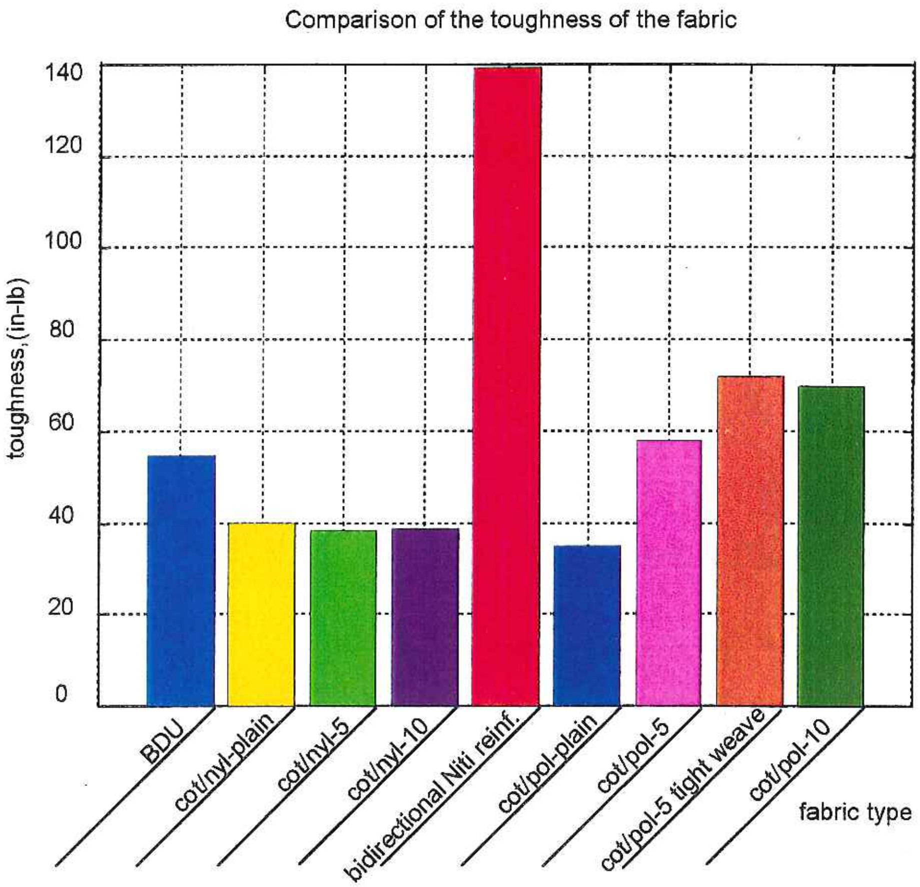


Figure 14. Tongue Tear Test results comparison chart

Table 2. Tongue Tear Test Results

Specimens	Peak Toughness at 7.0" Tear, lb.	Standard Deviation	Peak Load during Tear, lb.	Standard Deviation
BDU fill	54.76	5.24	13.74	0.66
Cot/Nyl Plain	40.08	1.06	10.10	1.76
Cot/Nyl-Niti-5	38.16	2.29	10.52	0.43
Cot/Nyl-Niti-10	38.54	2.47	9.97	2.54
Cot/Nyl-Niti-20 Bi-direct	139.0	16.47	30.00	3.32
Cot/Pol-Plain	35.11	1.97	9.41	0.57
Cot/Pol-Niti-5	58.02	5.37	18.51	2.23
Cot/Pol-Niti-5 tight weave	72.7	8.68	24.4	1.75
Cot/Pol-Niti-10	70.34	4.55	21.36	0.55

2.4. Fabric Breaking Strength in the Modified Grab Test

The Modified Grab Tests were performed on 4-by-6-inch specimens, with the longer side parallel to the direction of load application. For the Nitinol-reinforced fabric the load was applied in the direction parallel to the Nitinol filling yarns. The specimens were clamped into the tensile testing machine with 1-by-3-inch clamps instead of the more conventional 1-by-1-inch geometry. For this reason, the Grab Test results are not directly comparable to the Mil-Spec standard. As in the Tongue Tear tests, if the fabric performs as well or similar to the BDU fabric, we can expect that it will meet the Mil-Spec breaking standard. Test details are in Chapter 5.

The Grab Test, as given by standard ASTM-D5034, involves finding the amount of force to break the fabric specimen in simple tension. As the fabric is pulled, the force reaches a maximum, which is called the breaking strength. Grab Test results are reported as force versus extension. Since larger grips were used (3x area), the breaking strength will scale up as more material is pulled into the tensile action. Also, the fabric was pulled in the fill direction for all of the Phase I testing. Therefore, 270 lb. of breaking strength, or 3 times the Mil-Spec fill direction standard, is a reasonable approximation for the minimum breaking strength of the BDU fabric.

Grab Strength Definition: Grab strength is the average force required to break 3 inches of fabric while pulled by 3-inch wide grips.

Figure 15 shows the Grab Test load vs. elongation response of the cotton/poly family of fabrics and the BDU fabric. The cot/pol-5 and cot/pol-10 with 0.005" dia. Nitinol has a comparable breaking strength with the BDU fabric. Other observations are included on the next page.

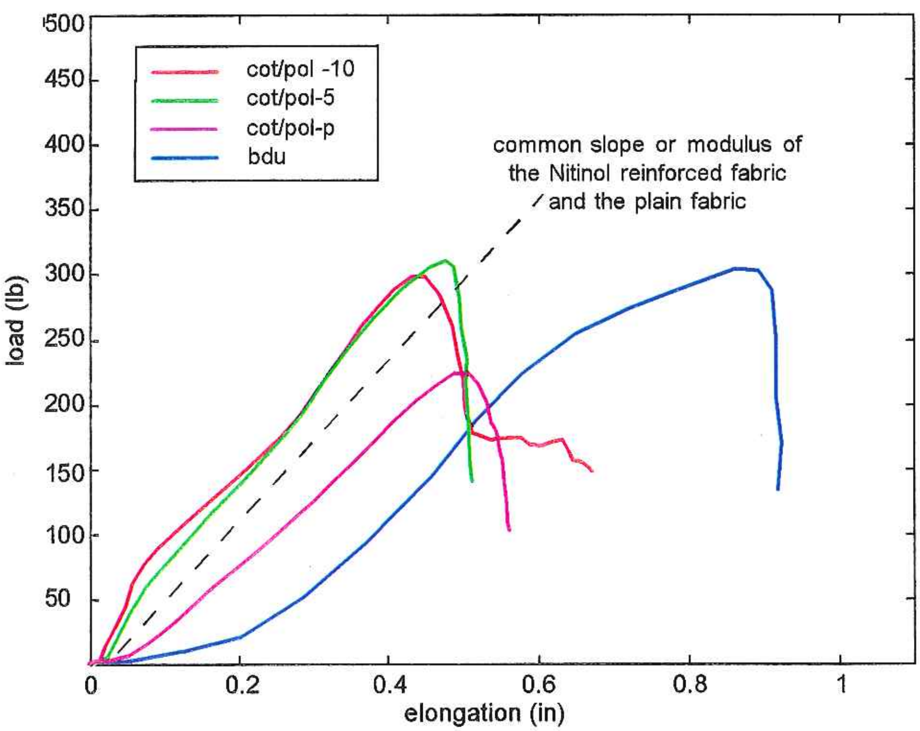


Figure 15. Grab Test results for cotton/polyester-based fabric

- The breaking elongation level for the cotton/poly based fabrics is, however, much lower than the BDU fabric. This is a property of the cotton/polyester yarn and not of the Nitinol.
- After failure of the host cot/pol yarns, the Nitinol fibers remain intact and bridge the breaks after the surrounding host cotton/poly yarns fail in tension.
- Comparing the cot/pol-5 and cot/pol-10 to the baseline cot/pol-p (Fig. 15), it is clear that the Nitinol reinforcement at 0.005" increases breaking strength by 50% over the plain fabric.
- If one assumes that Nitinol increases the BDU fabric's strength by the same margin, the true BDU fabric may show increases of 33-50% with Nitinol reinforcement.

Flexibility or stiffness is an important performance issue illustrated by the Grab Test. For the Nitinol-reinforced fabric to be as comfortable as the current BDU Fabric, the slopes or moduli of their load-elongation curves must be similar. For the curves in Figure 15, a common slope or modulus line has been sketched for the materials. Although the materials end up at different breaking strengths and elongation levels, the general slope to get there is very similar. This means that the Nitinol reinforcement will enable the same ease of stretching that the current BDU fabric allows. Having common or similar slopes in the tensile test is an important factor for judging the materials.

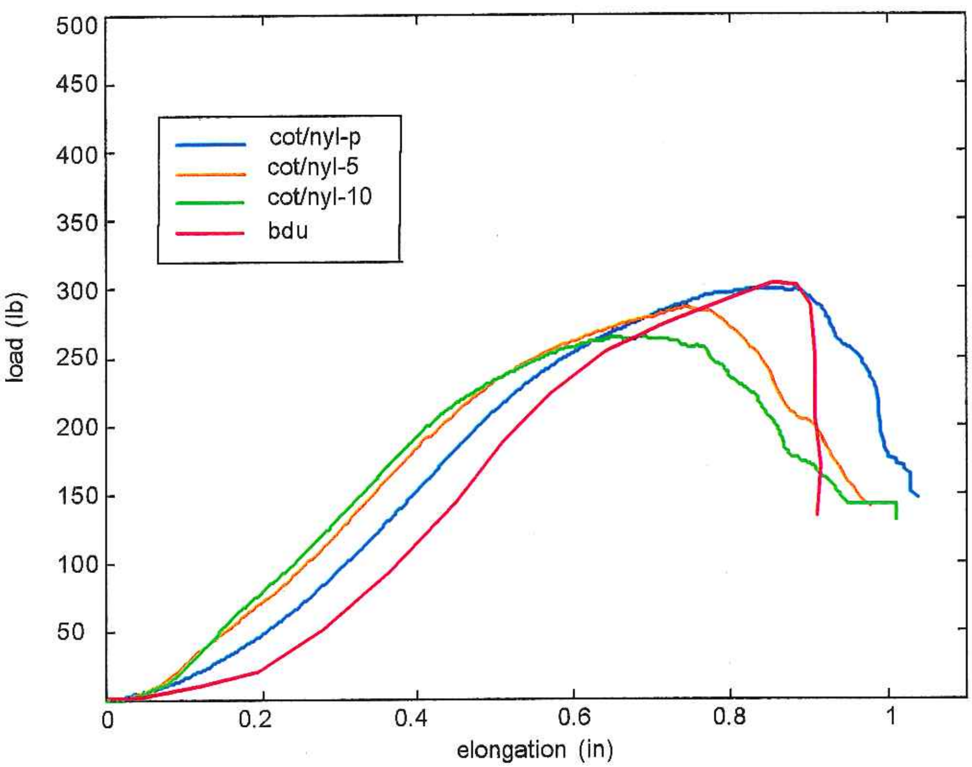


Figure 16. Sample Grab Test data for cotton/nylon-based fabrics with BDU fabric

Figure 16 shows sample Grab Test data for the cotton/nylon family of fabrics with the BDU fabric. Figure 17 shows all of the data for the Grab Tests. As explained in an earlier section, since the Nitinol in the cotton/nylon was 0.003" diameter, it did not increase the breaking strength. As Figure 16 indicates, the cot/nyl-p fabric imitates the breaking strength and tensile behavior of the BDU fabric quite well. The 0.003" diameter Nitinol does little to change the

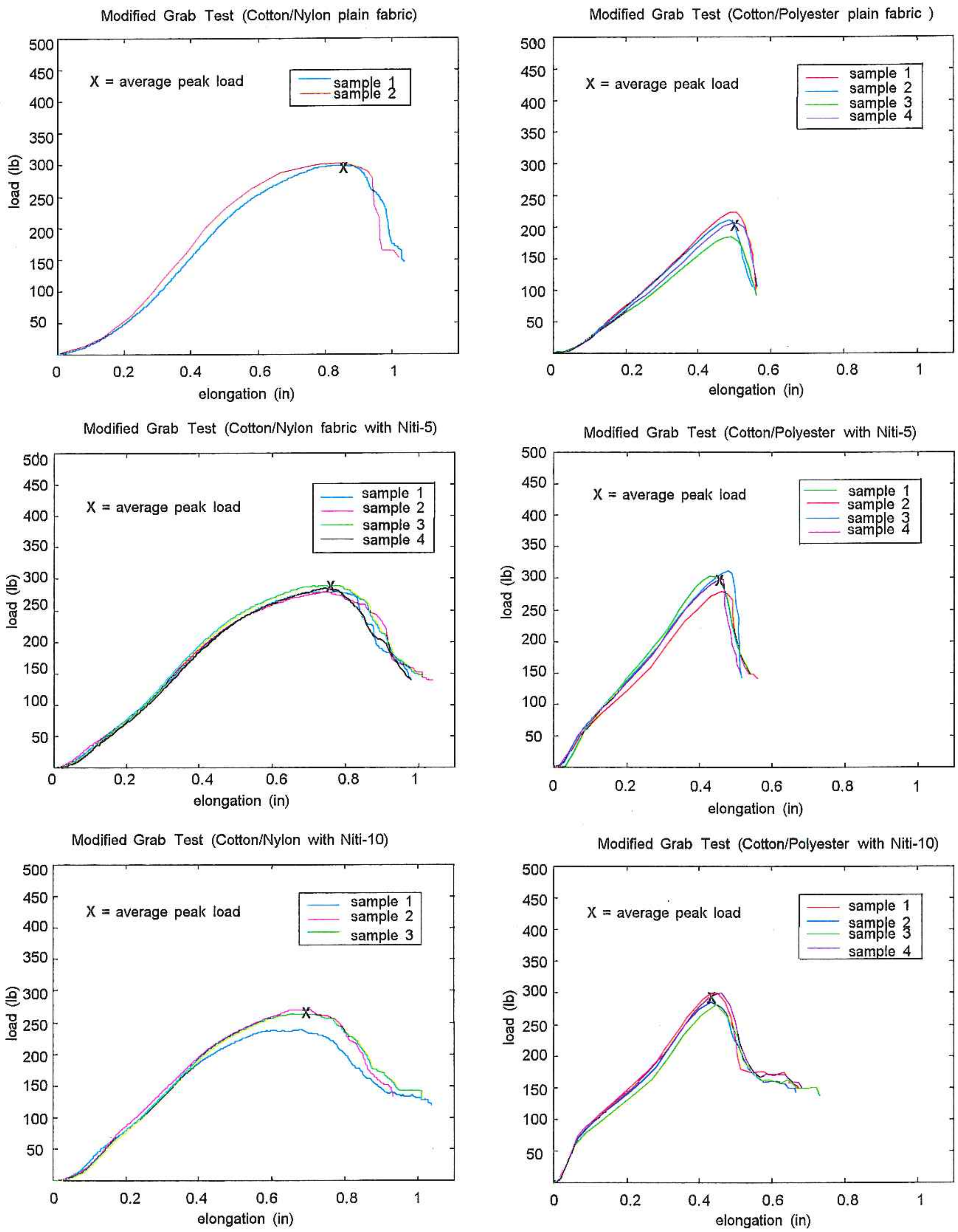


Figure 17. Individual Grab Test results for all fabrics tested

stretching of the fabric at 5 or 10 fibers per inch, indicating that the comfort level of the fabric is virtually unchanged. The 5 or 10 fibers per inch of the 0.003" Nitinol improve cutting resistance while not affecting the tear or break response.

Additional Observations from Grab Test Fabric Results

After calculations and visual investigation of the fabric geometry through the microscope it was determined that the diameter of the 0.003" Nitinol fiber is approximately three times less then the diameter of the cotton/nylon blend yarn (≈ 0.0098"). The increase of the size of the cotton/nylon yarns most likely occurs during washing and finishing of the fabric. Any introduction to moisture causes both the mass and the volume of the yarns to increase. By measuring the density of the plain fabric and Nitinol-reinforced fabric it was found that Nitinol lowers the density of the reinforced fabric. As mentioned earlier, the change in diameter of the finished fiber and the tightness of the finished weave leads to the conclusion that the cotton/nylon yarns are stronger than the 0.003" Nitinol when encased in the fabric.

Understanding the issues that occur during the tensile breaking process is important for improving the fabric. Table 3 shows the tabulated data for the Grab Test breaking force and elongation. As indicated by the data, the elongation is common between families of fabric and the strengths are higher for the fabrics reinforced with 0.005" Nitinol.

Table 3. Grab Test results

Specimens	Avg. Peak Load (lb.)	Standard deviation	Avg. elongation/ gage length (%)	Avg. Secant Stiffness (lb./in)
BDU fill	309.1	6.3	0.29	1065
Cot/Nyl Plain	294.0	9.4	0.29	1024
Cot/Nyl with Niti-5	283.7	4.8	0.25	1135
Cot/Nyl with Niti-10	258.0	14.5	0.23	1122
Cot/Pol Plain	205.3	14.5	0.16	1258
Cot/Pol with Niti-5	300.7	21.3	0.15	2005
Cot/Pol with Niti-10	311.1	9.3	0.15	2130

2.5. Fabric Density Test

The densities of the Phase I sample fabrics and the BDU fabric were calculated by measuring a specified area of the sample and scaling it to a square yard area. Table 4 gives the measured values of the areal density. According to military specifications, the weight of the fabric should fit in the range of 6-7 oz/sq. yd. Table 4 indicates that all the values of the areal density of produced fabrics are in this range.

As indicated in earlier sections, the 0.003" diameter Nitinol did little to increase strength because of the fact that it is actually lighter and smaller in diameter than the host fabric. This is manifested in the areal density data in Table 4. The fabric with 0.003" Nitinol reinforcement is lighter than its plain host fabric (cot/nyl-p). The fabric with 0.005" diameter Nitinol is actually heavier than its plain host fabric (cot/pol-p) but still within the Mil-Specifications.

Table 4. Density of the fabrics produced

Fabric type	Density (oz/yd^2)
BDU (Rip-stop)	6.65
Cot/Nyl Plain	7.00
Cot/Nyl with Niti-5 (0.003")	6.27
Cot/Nyl with Niti-10 (0.003")	6.75
Cot/Nyl with Niti-20 (0.005") Twill	6.96
Cot/Pol Plain	6.08
Cot/Pol-5-Niti/in. (0.005")	6.75
Cot/Pol-10-Niti/in. (0.005")	7.03
Stainless steel screen	4.48

3. Identification of Fibers/Fabrics Used in Military and Protective Clothing

This section reports the efforts of DSM-SAE engineers towards identifying potential fabrics and yarns that can be used as the basis of the protective BDU Fabric. A wide selection of potential yarns and fibers were investigated as the initial step in the Phase I project. The current cotton/nylon intimate blend yarn from Greenwood Mills was chosen along with a cotton/polyester yarn from Fabric&Yarn Associates as the basis of the protective clothing. It is noted that the Phase I effort involved looking at the feasibility of improving current BDU fabric with only shape memory alloy reinforcement. Phase II may involve investigating other reinforcement fibers in addition to the shape memory alloy. DSM-SAE engineers performed a literature review to determine mechanical properties of reinforcing materials to estimate the improved response. Additionally, testing of the individual yarns or fibers was performed to give insight into the experimental response.

3.1 Important Conclusions from the Fiber/Yarn Study

From Current Yarn and Fiber Testing Results

- Phase I fabrics will be based on a cotton/nylon that imitates current BDU fabric.
- Cotton/polyester will be used as an alternative for cotton/nylon in some of the testing.
- Nitinol 0.003" has a similar secant modulus to the cotton-based fabrics.
- Nitinol 0.005" has a slightly stiffer secant modulus than the cotton yarns.
- Nitinol 0.003" is stronger than the yarns under pure tension for 1" long specimens.
- Treating Nitinol to obtain maximum superelastic properties depends on the temperature and stress history of the fiber.

From Observations of the Yarn and Fiber Testing

- Differences in raw cotton/nylon and BDU fill fiber indicate that the automatic weaving process causes a reduction in ultimate strain or a shortening of the unraveling process.
- Finishing the fabric makes the fibers shorter, thicker and hence stronger.
- The cotton/nylon and cotton/poly yarns failed by fraying and separation of the filaments.
- Cotton/nylon is stronger than Nitinol 0.003" for very short lengths like those found in the fabric but weaker than Nitinol 0.005".
- Since cotton/nylon fails by unraveling in long lengths and by breaking in short lengths, the tear strength of the fabric is dictated by yarn breakage.

From Background Literature

- Kevlar®, Spectra® polyethylene, and stainless steel are not compatible with BDU fabric because of lack of flexibility and low elastic strain.
- Conventional metallic reinforcement decreases fabric flexibility and fails by metal fatigue.
- Fine diameter fibers in Kevlar® and Spectra® yarns provide little resistance against cutting.
- Superelastic Nitinol has one of the highest levels of pure elastic strain recovery for all materials except elastomers.

3.2. Background Data for Fiber and Yarn Performance from Literature Review

The field of protective clothing includes a wide range of materials and fabrics used in various industries. Protective clothing fabric includes high strength organic fibers such as aramid, nylon,

UHMW polyethylene, and polypropylene. Some of the names of the high strength fibers include Kevlar®, an aramid fiber from DuPont Corp., and Spectra®, an UHMW polyethylene fiber from Allied Signal Corp. Disadvantages that can plague these fibers include: very fine yarn diameter, which does not resist pure cutting very well, high stiffness, which means poor flexibility, and inadequate resistance to environmental effects. Since the fibers have performed well under some applications, it is appropriate to investigate their record of performance in the literature. Data for different fibers is shown in Table 5. The response of Nitinol-SMA is compatible with the cotton/nylon compared to the Kevlar®, Spectra® Polyethylene, and stainless steel in terms of modulus and ultimate strain. The Nitinol appears to be the most compatible reinforcement to the cotton/nylon because of its low secant modulus and high ultimate strain.

Table 5. Properties of different fibers

Fiber/yarn	Density	Young's modulus		Tensile strength		Ultimate Strain	Tenacity	Relevant Characteristic
	g/cm^3	Msi	GPa	Ksi	GPa	%	g/denier	
Fiberglass E-Glass	2.49	7.4 – 10	51-70	500	3.4	3.0	15	High strength, Low strain
Aramid (Kevlar®-149)	1.47	26.32	175	507.3	3.45	1.9	30	High strength, Low strain
Nomex	1.4	2.5	17	98.2	0.67	22-23	5.4	Medium strength, High strain
Graphite	1.78	29	200	300.5	2.07-2.3	1.5	13	High strength, Medium strain
Nylon 6.6	1.13	0.4*	2.76	86-134	0.58-0.91	16-28	5.9-9.2	Low strength, Very high strain
Nitinol	6.0	1.3*	45-70	200-260	1.6	20	3.1	High strength, High strain
Polyethylene	0.97	0.27-0.99* (16.9)	1.8-6.7	55-98 (441)	0.37-66	10-20	4.5-8	Low strength, Very high strain
Cotton	1.52	1.2*	8.3	80	0.5	3-7	3.0-4.9	Medium strength, low strain
Steel	7.8	30.4	210	512	4.25	2	3.5	High strength Low elastic strain
Polyester	1.12-1.46	1.1*	7.8	111-138	0.75-0.93	10-14	6.3-7.8	High strength, Low strain

Sources: S.B. Warner, *Fiber Science* (1995); E.R. Kaswell, *Wellimgston Sears Handbook of Industrial Textiles* (1963); Internet Website, *WSU CME Properties Tables: Organic Fibers*, http://engrweb.winona.msus.edu/docs/organic.htm.
*Secant Modulus: the ratio of change in stress to change in strain between two points on a stress-strain diagram

Fine conventional metallic fibers such as stainless steel may be added to organic fiber fabrics to improve the cutting and puncture protection. Conventional metallic fibers, however, greatly decrease the flexibility of the protective clothing. Flexing required of the fabric can also lead to fatigue failure of the metallic fibers. The superelastic Nitinol fibers proved to be stronger yet more flexible replacements for the stainless steel as additives to organic fiber fabrics.

The obvious candidate for the Phase I testing samples host or baseline fabric is the current cotton/nylon blend used in BDU fabric. Various types of reinforcement might be added to it to yield the desired response while maintaining the general desired performance from the cotton/nylon. Since nylon has much higher energy absorption than other synthetic fibers, it is a good baseline fabric to be compatible with the superelastic Nitinol additions. Nylon also maintains its properties in repeated stressing and is very good in abrasion resistance, flex life, impact loading and dimensional stability. Cotton/polyester was also used as a baseline fabric for

the Phase I test samples. It has similar properties to cotton/nylon but without the higher tenacity and without the colorfastness required in the BDU application.

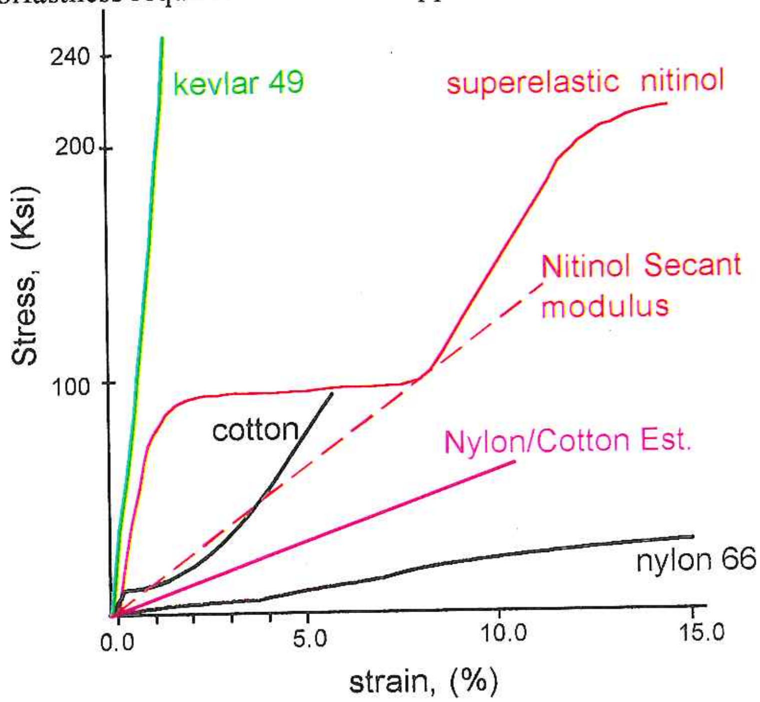


Figure 18. Stress-strain relations for different fibers

The estimated secant modulus of the cotton/nylon blend is shown in Figure 18 with the modulus data for the Nitinol and the Kevlar®. Stainless steel is similar to Kevlar® in modulus and is not shown for clarity. This initial modulus data was taken from the literature and calculated using the rule of mixtures approach. It is an approximate curve derived using the rule of mixtures and the secant modulus of the two constituents. The optimal secant modulus for an additive would lie parallel or on top of the cotton/nylon blend line. In this fashion, the additive has the same flexibility and stiffness of the host cotton/nylon. Since the Nitinol's secant modulus is slightly stiffer, the Nitinol diameter was lowered to be comparable to the cotton/nylon blend.

Figure 19 shows the elastic nature of the various fibers that might be used in protective clothing along with the level of elastic response, delayed elastic recovery, and permanent set. A high level of pure elastic response is advantageous, because it means that the fabric stretches and quickly returns. A high level of delayed recovery indicates that the fabric may get stretched and become "baggy" on the wearer until it is washed or relaxed. Poor fit and uncomfortable use can result in "baggy" or stretched uniform fabric. Superelastic Nitinol has one of the highest levels of pure elastic strain energy recovery for metals and organic polymer fibers. After Nitinol is strained beyond the first plateau (in Figure 18), it begins to strain with a permanent set. Since the cotton/nylon fractures beyond this strain level, the permanent set is not critical to design.

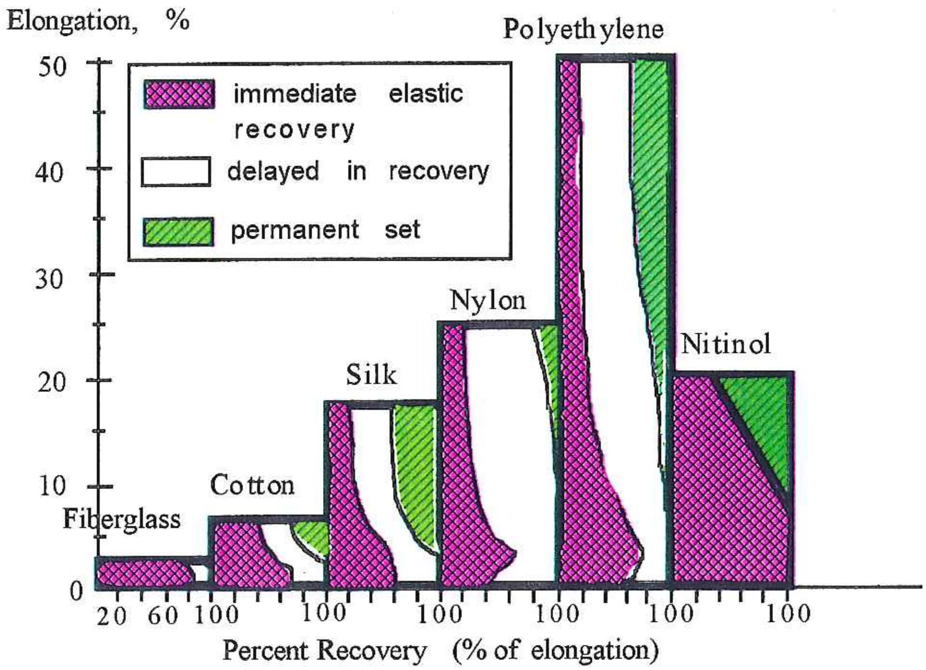


Figure 19. Recovery behavior of different fibers

<u>3.3. Experimental Testing of the Test Sample Yarns and Fibers</u>

To experimentally characterize the cotton/nylon, cotton/polyester, Nitinol and stainless steel used in the study, a tensile breaking test was performed on each type of fiber or yarn. Breaking strength and elongation data were determined by conducting a tensile test on each single yarn or fiber type using a "SATEC" tensile load frame with a 100-lb. load cell. A computer recorded instantaneous pulling force (load) versus fiber stretching (elongation). The resulting load-elongation curve for each set of fibers or yarns was plotted and is shown in Figure 20. Gage lengths of approximately one-inch long were used so that the test data can be readily changed to strain data. The tested yarns and fibers along with their labels include:

- 0.003" diameter stainless steel from Best Manufacturing (Dflexsteel);
- 0.003" diameter Nitinol (Nitinol 0.003)
- Unraveled yarn from BDU fabric fill direction (bdufill);
- Unfinished cotton/nylon yarn (cot/nyl raw);
- Unfinished cotton/poly yarn (cot/pol raw).

The following data can be gained from the yarn/fiber test results:

- ultimate strain
- ultimate strength
- secant modulus

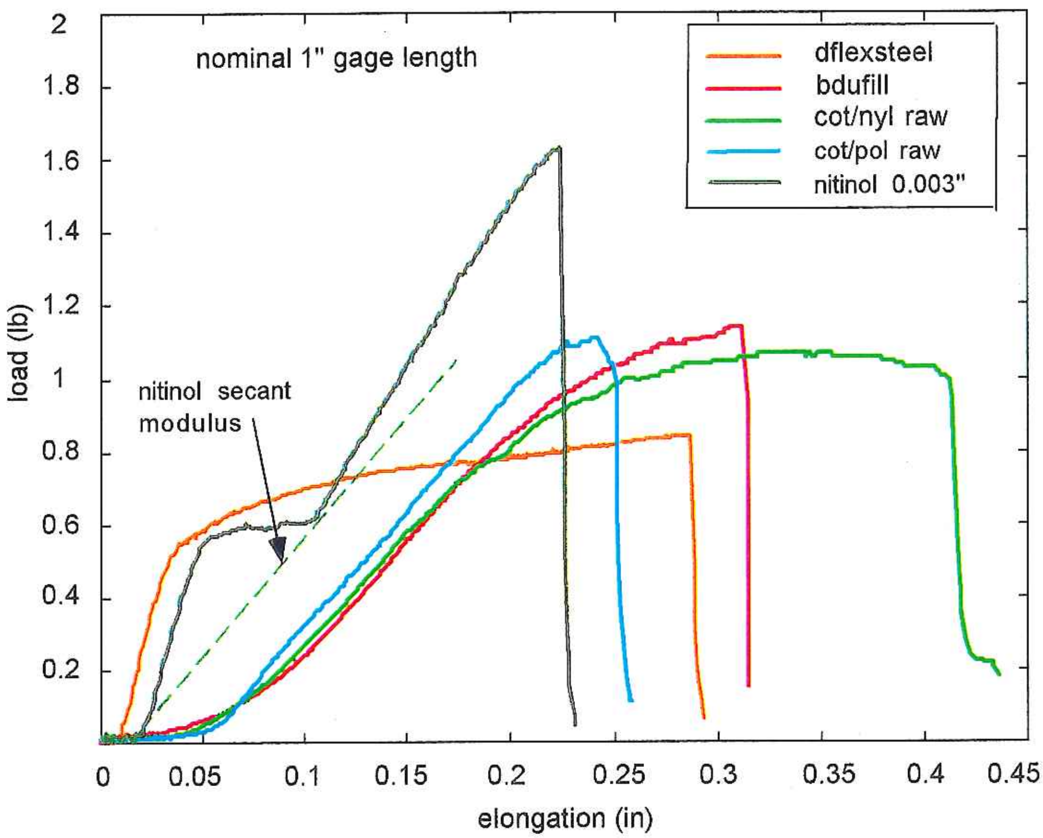


Figure 20. Typical response of the different fibers in tension

Figure 20 indicates an average or typical response taken from each set of tensile tests for the individual fibers shown in Figure 21. Important observations from Figure 20 include:

- The strain response and tensile response of the cotton/nylon and cotton/poly are similar.
- The cotton/nylon and cotton/poly proved to fail by fraying or separation of the filaments.
- Stainless steel fiber is tough (has high level of strain), but it is not very strong.
- Nitinol tended to fail at the jaws and can have a significantly higher response.
- Raw Cot/poly is much less tough than the comparable raw cot/nylon.

The shape of each fiber or yarn's load–elongation diagram is important in terms of the fiber's influence on such fabric properties as breaking and tear strength, energy absorption, dimensional stability, etc. Observations about the shapes of the curves in Figure 20:

- The cotton/nylon, cotton/poly and BDU fill have similar slope on the load-elongation curve.
- If a fabric has a lower slope, the fabric is less stiff.
- The Nitinol has a secant modulus with the same slope as the cotton-based yarns.
- The Nitinol has significantly higher strength than the other yarns.
- The finished cotton/nylon represented by bdufill unravels significantly faster than the raw fibers.

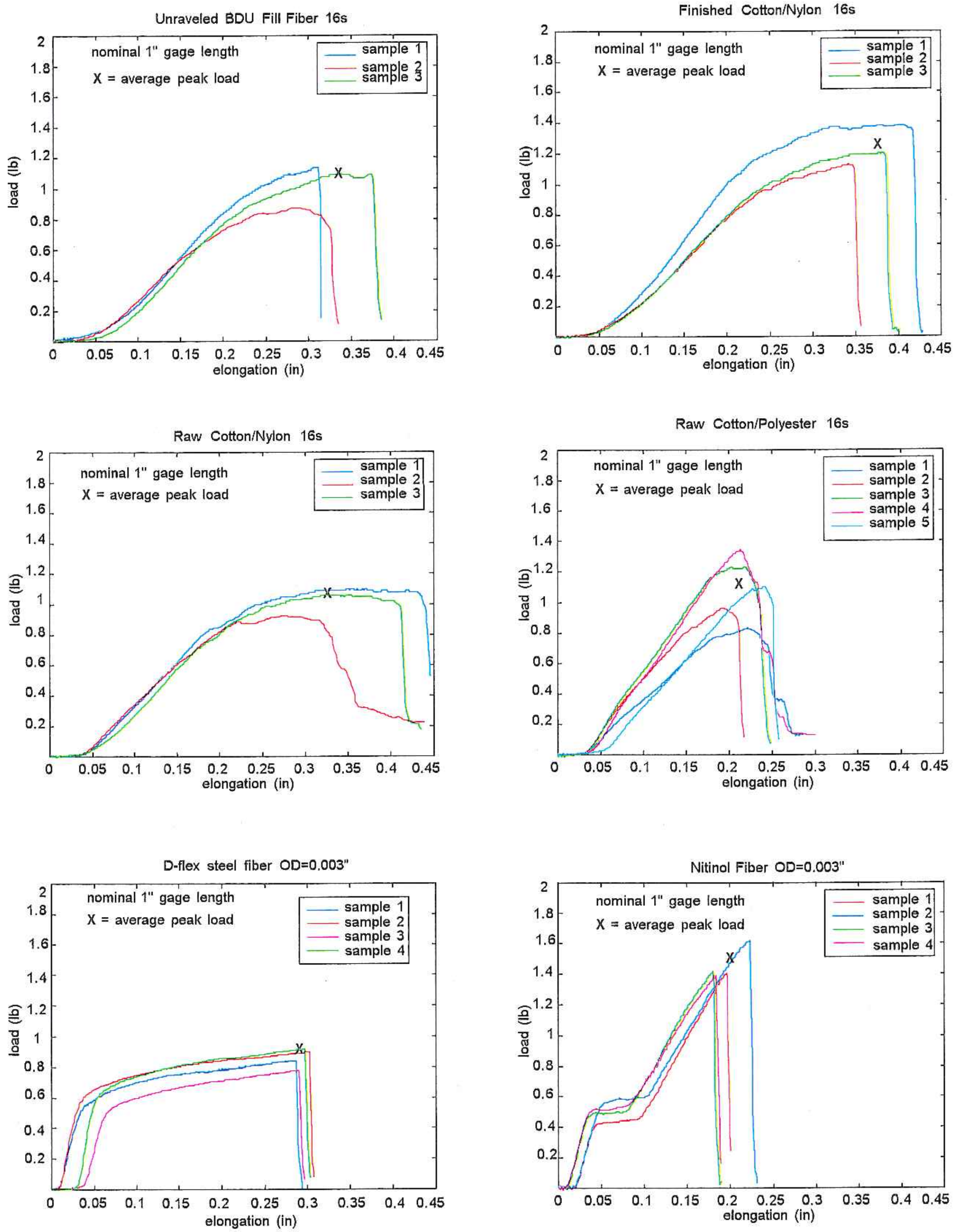


Figure 21. Tensile property tests: raw data for each of the different fibers

Unraveling of the Cotton Yarns vs. Breaking

One aspect of the yarn failure that is not indicated by the response is the nature of the failure.

- Since the cotton-based yarns fail in unraveling or untwisting, they will have higher strength if the untwisting is constrained.
- Locking the yarns into a fabric makes the effective gage length of the cotton-based yarns much shorter. Therefore, the yarns in the fabric will show a much higher strength than individual yarns.

For this reason, the cotton-based fibers in the fabric manifested higher strengths in the fabric than indicated in Figures 20 and 21. For the very short yarn gage lengths in the weave, yarn strengths end up being even higher than the Nitinol at the 0.003" diameter setting. Thicker Nitinol fibers at 0.005" diameter proved to be much stronger than the cotton-based yarns, and only at this diameter did the Nitinol significantly benefit the tear resistance. The effective diameters of the cotton/nylon yarns in the fabric proved to be approximately 0.010".

Table 6 gives a comparison of the breaking strength of several fibers from the experimental tests. Also shown is the peak strain as a percentage of the gage length. It is evident that the Nitinol is a high-performance fiber with extremely high breaking strength, almost twice as high as the Dflex-stainless steel. The cotton-based yarns have higher breaking strains as single fibers, since they unravel instead of break.

Table 6. Fibers chart

Fiber type	**Av. peak load, (lb.)**	**Peak elongation/gage length (%)**
Cot/Nyl raw	1.028	0.325
Cot/Nyl finished	1.234	0.374
Cot/Poly raw	1.092	0.212
Nitinol (0.003")	1.446	0.194
Nitinol (0.004")	2.259	0.204
Bdu fill (unraveled)	1.037	0.330
Bdu warp (unraveled)	1.309	0.480
Dflex- stainless steel	0.858	0.291

3.4. Treatment of Nitinol for best response

A short discussion is reported here on superelastic Nitinol treatments to yield the best response for use in the protective fabric. DSM-SAE engineers are proficient at setting the conditioning and processing of Nitinol-SMA to obtain the most effective response. Challenges that must be addressed and accommodated when using Nitinol include determining which processing temperature(s) and times yield the best properties. Almost all of the performance parameters for Nitinol materials are dependent on stress and temperature history. As an example, Nitinol can be brought into its superelastic stage by treating it at a high temperature (500^{0}C) after stressing the fiber by mechanical drawing. In order to obtain the best response, Nitinol fiber samples were heated at a high temperature for different lengths of time. The results of testing are shown in Figure 22. Nitinol samples that were treated for 15 minutes at 500^{0}C show a better response then the other samples (Figure 22).

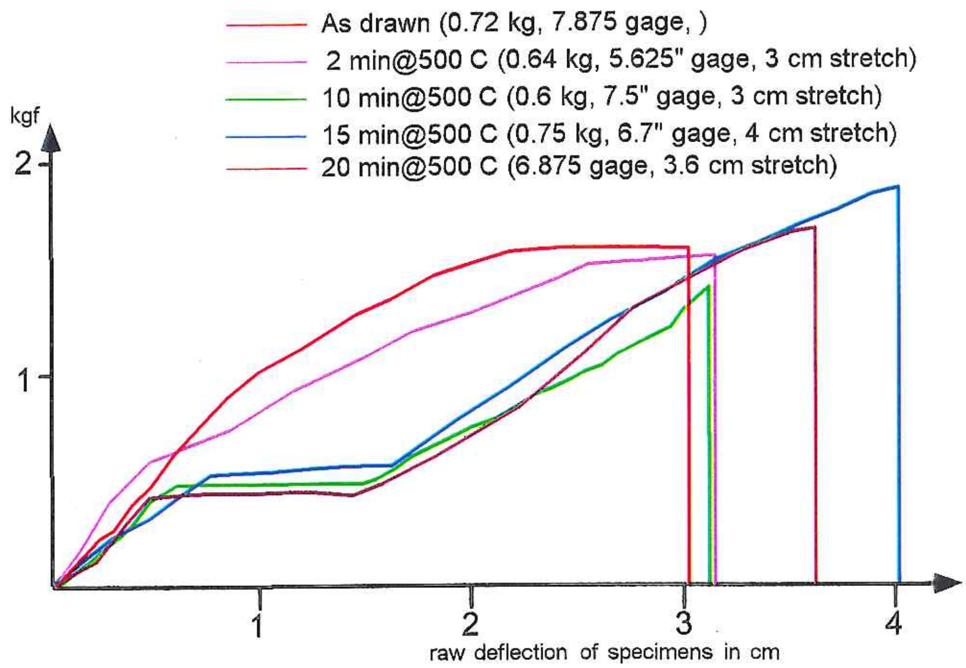


Figure 22. Testing the Nitinol for Breaking strength and Elongation

3.5. Bibliography

1. Kaswell E.R., "Wellington Sears Handbook of Industrial Textiles", Wellington Sears Company Inc., 1963
2. Kaswell E.R., "Textile Fibers, Yarns and Fabrics", Reinhold Publishing Corporation, 1953
3. Vigo T.L., "High-Tech Fibrous Materials", American Chemical Society, 1991
4. Warner S.B., "Fiber Science", Prentice Hall, 1995
5. Brown W.E., "Testing of polymers", John Wiley&Sons Inc., 1969
6. Lewin M., Preston J., "High Technology Fibers", Marcel Deccer Inc., 1989
7. Goswami B.C., Martindale J.G., Scardino F.L.,"Textile Yarns", John Wiley&Sons Inc., 1977

4. Industrial Partners and Commercialization

Representatives from various companies have been contacted to inform them of our research and solicit information from them about their interests and needs.

Military Fabric Production

Greenwood Mills – Gene Munns, Mike Kilkenney
The relationship with Mike Kilkenney and Gene Munns of Greenwood Mills has aided DSM in production of the reinforced fabric. Dr. Paine met with Gene Munns and has visited their facility. They have provided valuable insight into the current fabrication methods and they gave us a large enough sample of the cotton/nylon yarn for use in fabricating the test samples.

Delta Mills – Doug Gantley
Delta Mills may eventually be willing to consider integrating some of our Nitinol material into the cotton/nylon twill. Right now we are working on a relationship with them for Phase II.

Fiber Development

Du Pont Corp. – Principal Contacts: V.J. Kumar
Dr. Paine and Dr. Kumar had a friendly conversation about the current research program at DSM and about the potential for using Nitinol reinforcement with their materials. Dr. Kumar showed some academic interest in seeing the results. He may have interest in combining some of the fibers with Nitinol once he sees the Phase I results.

Dixie Yarns – T.M. Sutter and Catherine Vreeland
Dr. Paine met with T.M. Sutter the Vice President of Product development to discuss core-spinning yarns around Nitinol to aid in integrating the Nitinol into fabric for the military and protective clothing. The diameter of the yarns is such that the weaving process would require an increase in the diameter to give the fibers some loft and to aid in air-jet weaving.

Nitinol Fibers and Products

Fort Wayne Metals – Scott Shoppell
Fort Wayne Metals is a leading supplier of fine-drawn Nitinol wire and cable. They produce much of the Nitinol used in the actuator, orthodontics and eyeglass market. They have supplied us with wire and thread for our samples. They have the ability to produce high volumes.

SMA Corp. – Daryl Hodgson/Carolyn Rice
A supplier of Nitinol finished products. SMA has a large market share of Nitinol in actuators and orthodontic designs.

Memry Corp. – Zaffir Chaudhry
Memry produces a large number of high volume Nitinol and shape memory alloy parts for the medical markets. We may benefit from their marketing of Nitinol-reinforced products.

Testing of Fabrics

Florida State University Textiles Science Dept. Head, – Prof. Rinn Cloud
The textiles department has aided DSM-SAE engineers in performing the testing for the Phase I project. Prof. Cloud is very interested in collaborating on the Phase II and aiding DSM again for the testing and production of the Phase II prototypes. They may also be able to help in using Nitinol for reinforcing some non-woven protective fabrics. FSU will be a Phase II subcontractor because of their extensive testing facilities and expertise in Protective Fabric Development.

Best Manufacturing Company - Rick Pewitt
Best Manufacturing makes a wide variety of gloves for the protective clothing field. Best does almost everything themselves in the glove production. They have a line of gloves that makes use of stainless steel filaments that are 0.003 inches in diameter. The Nitinol-reinforced fabric should be able to greatly enhance their product line by giving them the flexibility that they desire and the strength of the Nitinol. They will be a good Phase II commercialization partner.

Additional Commercial Contacts

Kimberly Clark Corp. - Roseanne Kaylor
A recent conversation with Roseanne Kaylor of Kimberly Clark Corporation near Atlanta generated an interest in Kimberly Clark's non-woven textiles division. Ms. Kaylor is a researcher at the Kimberly Clark research Center and DSM will be working with them in the Phase II to determine if collaboration would be valuable and warranted.

Chairman of the Chainsaw Protection Sub-Committee ASTM - Vincent Diaz
He gave our engineers two business cards, one for a chainsaw protective clothing company and another for a thread manufacturing company of which he is the president. He found the Nitinol integration idea particularly interesting for puncture resistance in chainsaw chaps.

Modern Headware, LTD. - Darko Gorenc
This is a Canadian chainsaw protective clothing company that uses glass and nylon reinforced fabric. Mr. Gorenc sent us some samples during the project to test, but we have not yet completed the testing due to time constraints. He seemed very interested in our idea and recommended Martin Tex Inc. for weaving samples for us.

Canadian protective clothing consultant - Gary Isberg
Mr. Isberg is an engineer and a part-time consultant for Darko Gorenc's company. He has been active in developing methods for testing fabrics against the damage of chainsaws. He was also interested in the Nitinol fabric idea and was curious about using a NiTi fabric layer as a sub-layer for a bullet proof vest to minimize trauma. He thought the Nitinol fabric would be highly appropriate for puncture/stab wound resistance.

DuPont Advanced Fibers Systems - Navin Tejani
Specializes in area of Advanced Fibers and has interests in all sorts of applications that related to this area. DuPont's site in Richmond makes fibers for composites and protective clothing.

5. Test Methods for Fabric Evaluation

DSM engineers examined several potential test methods for testing the breaking strength and tear resistance of the BDU fabric with Nitinol reinforcement. DSM obtained the methods by examining the ASTM standards and reading the pertinent literature. A description of the test methods used in the Phase I testing and other important methods is presented.

5.1 Cut Resistance Test Methods

No military standard currently exists for the cut resistance of BDU fabric. Therefore, the ASTM F1790 standard for cut resistance was followed using an ASTM recommended machine at the Best Manufacturing Labs in Menlo, GA. (*Standard Test Method for Measuring Cut Resistance of Materials Used in Protective Clothing, F1790)*

This standard is used to measure a fabric's resistance to cut-through. It requires a costly machine that either uses a rotary cutter and a circular mandrel or a crank-driven linear cutter and automatic caliper to measure how long it takes to cut through a thickness of fabric (Figure 23). The fabric sample is cut with an increasingly higher load on the blade until the blade goes through after 1 inch or 25 mm of travel. When penetration of the sample occurs, the tester automatically stops.

A picture of the tester with a sample piece of BDU fabric installed and in position to be cut is shown in Figure 23. The method worked quite well and was able to yield accurate data.

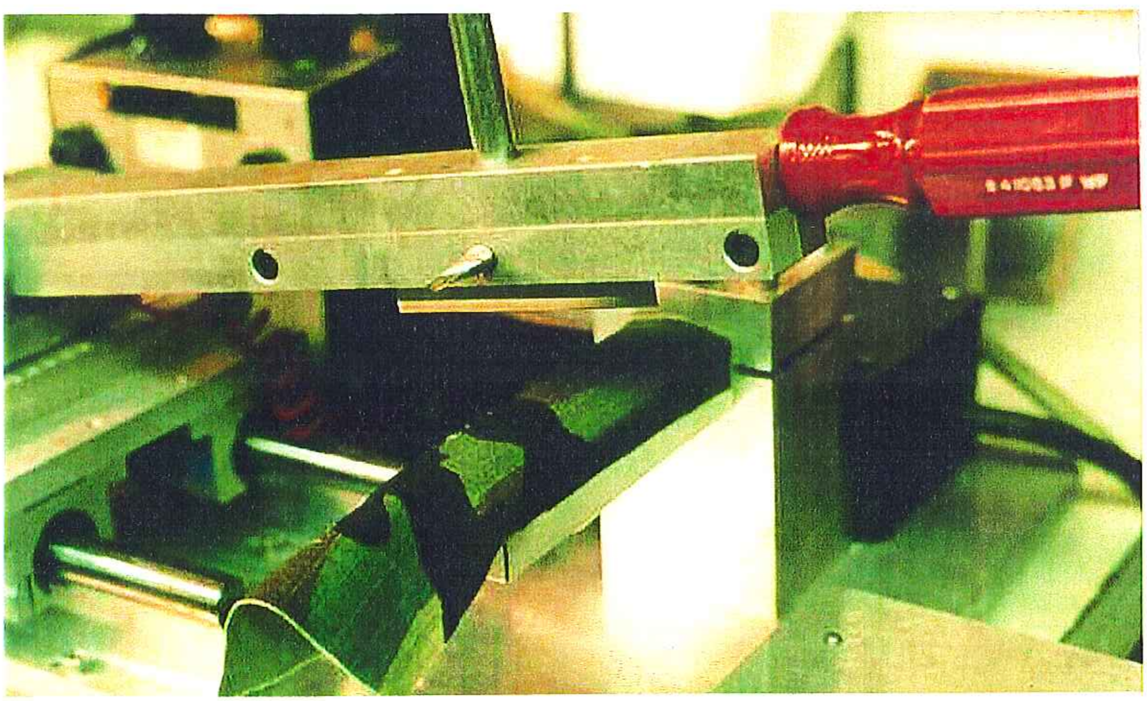


Figure 23. Cut Tester with a sample of BDU rip-stop fabric

5.2. Tear Resistance Test Methods

Three types of tear tests are widely used. They are briefly described in this section

Elmendorf Test

The *Tear Resistance of Woven Fabrics by Falling-Pendulum ASTM-D1424* standard uses the Elmendorf Tester to tear the fabric and measure the falling weight required to do so. The military standard for tear resistance uses the Elmendorf tester (Figure 24), following ASTM Standard D1424. This standard yields a single value for the amount of tearing load needed to advance a tear but yields no data about the way the tear progresses or why. DSM engineers have decided to not perform this test for Phase I because of reasons described above. The way the tear progresses and the contribution to toughness from the reinforcement are readily observed using the Tongue Tear ASTM standard test, D2261. In Phase II, the Elmendorf Tester will be used for appropriate qualification of the prototype fabrics for Mil-Specs.

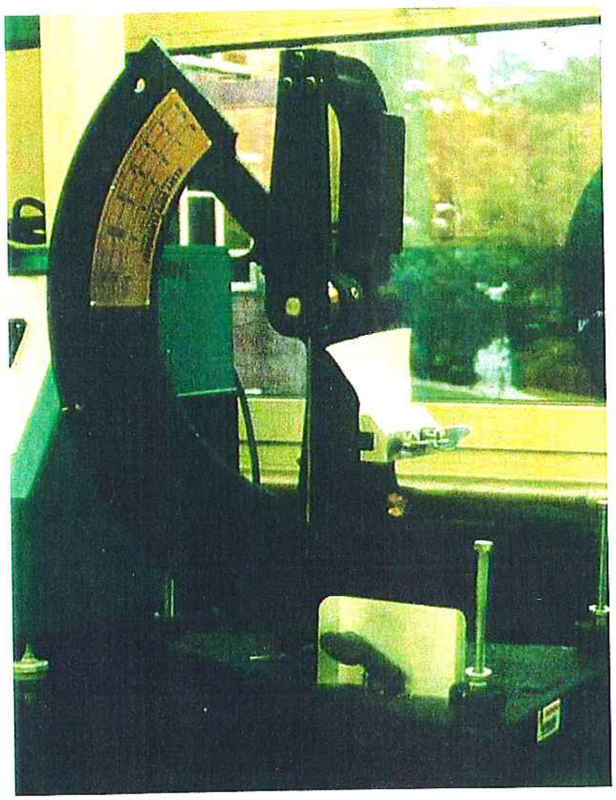


Figure 24. Elmendorf Tester

Tongue Tear

DSM-SAE engineers chose to use the Tongue Tear method in order to observe the load changing as the tear advanced through the reinforcement (*Tongue Tear Test, ASTM-D2261)*. The test procedure for the Tongue Tear Test follows ASTM standard in that it involves finding the amount of force that is necessary to advance a tear in the specimen. In the Tongue Tear Test an 8-by-3-inch specimen is cut so that the yarns to be ruptured during the tear lie in the shorter dimension. As the jaws move apart, the specimen assumes a configuration typified as shown in

Figure 25. Each yarn is subjected to progressively increasing tension. The tearing action is manifested on the tensile tester recorder as a diagram of progressively increasing and then sharply decreasing loads.

DSM engineers did not follow ASTM standard for the Tongue Tear Test in that they used different tensile tester specifications in the testing. The modified Tongue Tear Test was conducted using a "SATEC" hydraulic drive tensile machine. The specimens were clamped into the tensile testing machine with 1-by-3-inch clamps, as shown in Figure 25. The machine was operated with a rate of extension of 2 in./min.

Figure 25. "SATEC" tensile tester performing Tongue Tear Test

5.3. Breaking Strength Test Methods

Breaking Force and Elongation of Textile Fabrics (Grab Test), ASTM-D5034. The description of the ASTM standard is given below.

The breaking strength of a specimen is used both for quality control and as a performance standard. For the purposes where the fabric is subjected to tension, it is important to measure breaking strength. The Grab Test is only one type of the fabric strength tests that are commonly used. The test is performed on a specimen that is 4-by-6-inch and cut so that the direction of the test is in the longer direction.

Modified Grab Tests were performed on 4-by-6-inch specimens, with the longer side parallel to the direction of load application. For the Nitinol-reinforced fabric, the load was applied in the direction parallel to the Nitinol filling yarns. The specimens were clamped into the tensile testing machine with clamps with 1-by-3-inch dimensions instead of the more conventional 1-by-1-inch grip geometry. For this reason, the Grab Test results are not directly comparable to the Mil-Spec standard.

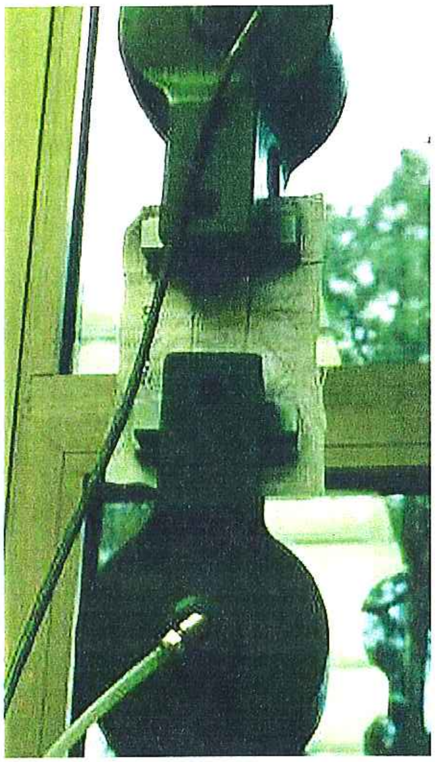


Figure 26. "SATEC" tensile tester performing Grab Test

The "SATEC" tensile tester performing Grab Test is show on Figure 26. The machine was operated with a rate of extension of 2 in./min. The specimens were loaded until the rupture occurred.

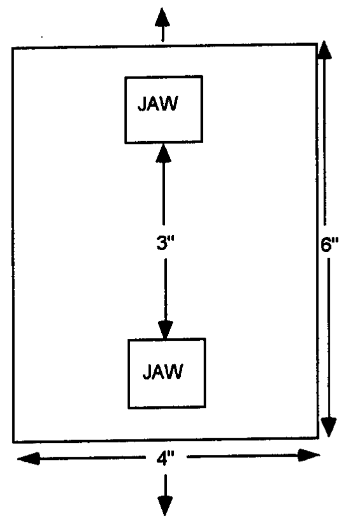


Figure 27. Schematic of the specimen for the Grab Strength Test

At the start of the test, flat jaws are used to clamp the fabric. When the jaws are separated, the trough-going yarns clamped in both jaws are subjected to tension.

DSM-SAE engineers made use of these four test methods to quantitatively and qualitatively determine the performance of the BDU fabric with and without Nitinol Reinforcement.

Other available methods that might be used in later testing:
Stall Inflated Diaphragm Method (Abrasion Test Method)
Stall Flexing and Abrasion Folding Bar (Abrasion Test Method)
Schiefer Uniform Abrasion Method (Abrasion Test Method)
Special Webbing Abrader (Abrasion Test Method)
Standard Test Method for Measuring Cut Resistance to Chain Saw in Lower Body (Legs) Protective Clothing, F1414

6. Fabrication of Nitinol-Reinforced Fabrics

An important issue for including Nitinol into the base cotton/nylon fabric is to optimize the method for incorporating the reinforcement. Since protective clothing commonly used by military are made from high strength woven fibers, various methods to weave the Nitinol into fabric were investigated. Originally, several major fabric suppliers were contacted about weaving the Nitinol and cotton/nylon fibers. Using a major fabric supplier proved to be infeasible because of manufacturer restriction on lot size and minimum order. Therefore, DSM-SAE used two private weaving services that worked closely with DSM-SAE engineers to produce a suitable fabric for the Phase I study. Fabrication methods and issues for Nitinol-reinforced fabric are described below.

6.1. Yarn Suppliers, Fabric Producers, and Weaving Contractors

Companies that specialize in yarn manufacturing and supplying were contacted for supplying the cotton/nylon for the samples. None could readily deliver anything other than cotton/polyester. For this reason, DSM-SAE relied on Gene Munns and Mike Kilkenney of Greenwood Mills for a sample of the yarn used in the BDU fabric for Phase I fabrics. Most of these companies could not supply the yarn for weaving, but they are considered as a good contacts for the future. The following yarn companies have been contacted and may work with us in Phase II. Dixie Yarn in Chattanooga has offered to core-spin cotton/nylon around Nitinol in preparation for using Nitinol in the shuttleless loom operations at Greenwood Mills and other large mill operations.

Yarn Suppliers and Researchers

Integrated Textile Systems – Paul Weber
Dixie Yarns – Katherine Vreeland, Tom Sutter
Unified Yarns – Allison Widdle
TNS Mills, Inc. – Glen Mac
EvenDale Mill – Don Cassel
Fabric&Yarn Associates – John Hodge
Dominion Yarn – Jeff Fisher
Coats&Clark Inc.
National Spinning Co. Inc.
North Carolina Spinning Mills Co. Inc.
Textile Fibers

Fabric Producers:

Private Weaver – Sharon Alderman
Complex Weaver – Judi Eatough
Greenwood Mills – Gene Munns
Delta Mills – Dug Gantly, Larry Howard
Fabric Developments – Mary Schafer
Martinex Inc. – Michael Loney

6.2. Weave Design for the Phase I Fabric Samples.

The weave for the Nitinol-reinforced samples was defined by using the basic plain weave used in the current BDU rip-stop fabric and adding reinforcements. Nitinol and other reinforcing yarns or fibers were added by simply replacing certain fill or warp yarns with the reinforcing fibers. Staying with a simple plain weave at approximately 50 yarns in the fill and 100 yarns in the warp made it easy to define a certain reinforcement density. For example, 5 Nitinol fibers per inch in the fill direction simple meant replacing every 10th fill yarn with a Nitinol fiber.

The Phase I samples were made at 8 to 10" wide and 2 yards long. Sample pictures for some of the fabric is shown in Figure 28. For the first set of reinforcements, Nitinol at 0.003" diameter was added to a cotton/nylon plain weave that matched the BDU rip-stop weave.

Cotton/Nylon Plain Weave
Plain weave, 52 yarns/in. in fill and 104 yarns/in. in Warp
Yarns: 20s 2-ply twisted warp yarns and 16s singles twisted in fill
Reinforcement: none
Finishing: wash, drip dry and iron flat.

Cotton/Nylon Plain Weave with 5 - 0.003" diameter Nitinol fibers/inch
Plain weave, 52 yarns/in. in fill and 104 yarns/in. in Warp
Yarns: 20s 2-ply twisted warp yarns and 16s singles twisted in fill
Reinforcement: Replace every 9th fill yarn with one 0.003" diameter Nitinol fiber
Finishing: wash, drip dry and iron flat.

Cotton/Nylon Plain Weave with 10 - 0.003" diameter Nitinol fibers/inch
Plain weave, 52 yarns/in. in fill and 104 yarns/in. in Warp
Yarns: 20s 2-ply twisted warp yarns and 16s singles twisted in fill
Reinforcement: Replace every 5th fill yarn with one 0.003" diameter Nitinol fiber
Finishing: wash, drip dry and iron flat.

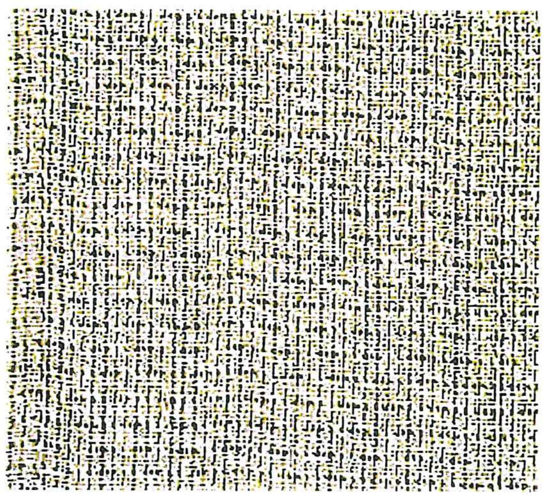
To improve the tear and grab strength, the Nitinol was increased in diameter to 0.005" so that it would be stronger than the fill yarns at short gage lengths. Cotton/polyester yarn was used in the second run because it was readily available and closely resembles the response of cotton/nylon.

Cotton/Poly Plain Weave
Plain weave, 52 yarns/in. in fill and 104 yarns/in. in Warp
Yarns: 20s 2-ply twisted warp yarns and 16s singles twisted in fill
Reinforcement: none
Finishing: wash, drip dry and iron flat.

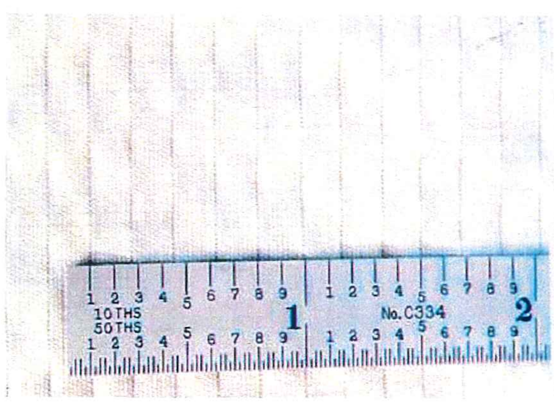
Cotton/PolyPlain Weave with 5 - 0.005" diameter Nitinol fibers/inch
Plain weave, 52 yarns/in. in fill and 104 yarns/in. in Warp
Yarns: 20s 2-ply twisted warp yarns and 16s singles twisted in fill
Reinforcement: Replace every 9th fill yarn with one 0.005" diameter Nitinol fiber
Finishing: wash, drip dry and iron flat.

Cotton/Poly Plain Weave with 10 - 0.005" diameter Nitinol fibers/inch
Plain weave, 52 yarns/in. in fill and 104 yarns/in. in Warp
Yarns: 20s 2-ply twisted warp yarns and 16s singles twisted in fill
Reinforcement: Replace every 5th fill yarn with one 0.003" diameter Nitinol fiber
Finishing: wash, drip dry and iron flat.

Cotton/Nylon Bi-directional with 20-0.005" diameter Nitinol fibers/inch
In order to put the Nitinol in both the warp and fill directions, it was determined that a twill type fabric would be most advantageous in using the Nitinol. A 2 over 2 twill was used with 20 strips of Nitinol per inch in the fill and 10 strips of Nitinol per inch in the warp. The base yarns were as in the cotton/nylon plain specimens.

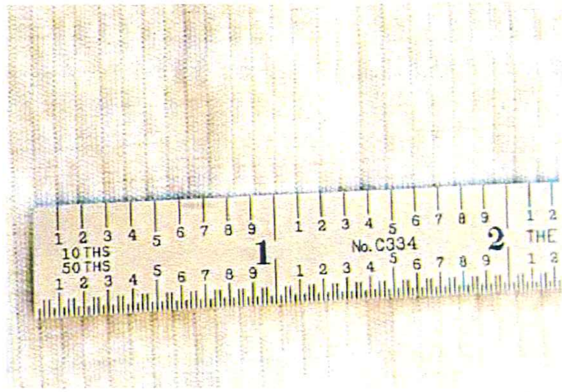


Cotton/Nylon bi-directional Nitinol (20 per inch) Twill Weave



Cotton/Nylon plain weave with Nitinol in fill direction (5 per inch)

Figure 28a. Samples of the protective fabric produced by DSM-SAE and weavers



Cotton/Nylon plain weave with Nitinol in fill direction (10 per inch)

Figure 28b. Samples of the protective fabric produced by DSM-SAE and weavers

Equipment used in fabric formation

Due to the specific properties of the Nitinol fiber a handloom was chosen in order to have complete control over the weaving process. A handloom would provide the fundamental capabilities of a power loom while providing the ability to control the speed and the placement of the yarns. In any weaving operation, it is important to maintain proper tension of the warp yarns. The high tension is particularly important when weaving the Nitinol due to its long elongation. The loom shown in Figure 29 was used to successfully weave Nitinol-reinforced fabric.

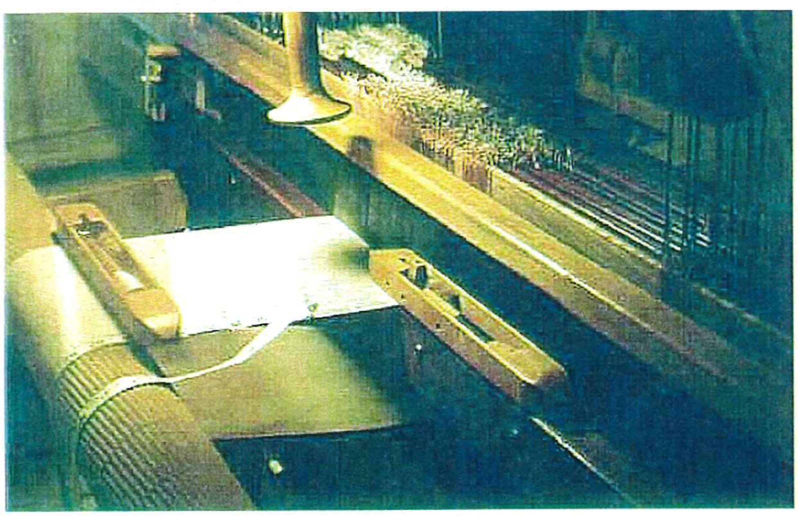


Figure 29. Conventional handloom used for weaving Nitinol with cotton/nylon-based fibers

7. Multi-Threat Capability

The objective of this task is to address different issues associated with the performance of Nitinol-reinforced fabrics with a cotton/nylon baseline in different environments. It is critical to assess the physiological, environmental, thermal and chemical effects on the various protective clothing to help the designers, developers and procurers provide the users with the protective clothing for their task. If such investigations are carried out within the development period, they can be of great value in providing the information whether the protective clothing will meet the requirements to protect the user from different occupational hazards.

All of the necessary features needed to protect the user in a certain occupation can be integrated into a single multi-threat fabric. By incorporating the Nitinol-reinforced fabric concept into a number of other categories of fabrics as a stand-alone customized fabric, it is possible to achieve an increased protection for occupational scenarios such as for flame resistance, thermal insulation, electrical insulation, chemical protection, and electrostatic dissipation.

7.1.Nitinol Multi-Threat Capability

A thorough investigation of the performance of superelastic Nitinol Shape Memory Alloys has been performed and the results of the investigation will be briefly described in this section.

Corrosion resistance
The Nitinol is very corrosion-resistant under both body fluid environments and many corrosive fluid environments. In this area, the Nitinol fibers may improve upon the organic fibers themselves which are susceptible to degradation by heat, body fluids and other corrosive fluids, ultraviolet light from the sun and other sources. Organic fibers are also susceptible to simple mechanical fatigue from brushing of the material with instruments and tools that do not affect the Nitinol fibers.

Thermal Resistance
Nitinol Shape Memory Alloys have outstanding thermal properties. They melt in the range of 1240^0-1310 ^{0}C. In addition Nitinol maintain good flexibility at temperatures down to –15 ^{0}C and as high as 90 ^{0}C.

Ultraviolet Resistance
Nitinol is unaffected by Ultraviolet rays and does not degrade like most synthetic polymer fibers.

Chemical Properties of Nitinol
Generally Nitinol Shape Memory Alloy has excellent stability to many chemical classes such as water, salts, organic acids, organic solvents, dry cleaning solvents, oxidizing agents (bleaches), reducing agents, gases and fuels (petroleum).

Previous testing performed on Nitinol showed the resistance of Nitinol alloys to high-velocity seawater, cavitation erosion, stress corrosion and crevice corrosion. Electrochemical measurements show that Nitinol fibers have a good resistance to pitting and chloride environment. Nitinol fibers show similar corrosion behavior to stainless steel. A naturally formed thin adherent oxide layer provides the excellent corrosion resistance.

Comfort
Nitinol Shape Memory Alloy has a smooth burr free surface after drawing and mechanical preparation. When used in the fabric is it very smooth. The Nitinol fiber itself should pose not threat to users comfort level. Care must be taken in Phase II to develop methods for incorporating seam ends and uniform aspects into the Nitinol fabric.

Biocompatibility of Nitinol
Nitinol Shape Memory Alloy has good biocompatibility. Histological studies showed newly generated bone tissue surrounding the Nitinol implants. Nitinol's good biocompatibility makes it an ideal biological engineering material. Especially for medical applications, its function cannot be compared to any conventional metal materials.

Electrical Resistivity
For high temperature forms of Nitinol (above 75 ^{0}C) = 82 microhm-cm, for low temperature forms (below 0 ^{0}C). This low level of resistivity makes the nitinol a very effective electrostatic discharge protective barrier.

Oxidation
Nitinol is highly resistant to oxidation at normal to 600 ^{0}C. It was observed that the rate of oxidation of Nitinol increases rapidly with increasing temperature from 600 ^{0}C to 1000 ^{0}C.

Hydrogen Absorption
It was found that Nitinol absorbed no hydrogen at temperatures up to about 500 ^{0}C.

These exceptional properties make Nitinol very advantageous for a wide range of application both in textiles and in medicine.

7.2. Cotton/Nylon Multi-Threat Capability

Most organic and nylon fibers are very susceptible to attack by the environment and human body fluids. Long term exposure to these threats is the typical means for wear in such fabrics. Cotton and Nylon fibers have relatively high strength, reasonable toughness, acceptable dimensional stability, low shrinkage, low moisture regain and quick drying ability, thermal stability, and resistance to stretching and shrinking, and many chemicals.

Thermal Resistance
Nylon fibers have outstanding thermal properties. They melt in the range of 400 ^{0}F, crystallize at 350-400 ^{0}F. Nylon fibers maintain acceptable strength at temperatures below freezing.

Chemical Resistance
Generally nylons have excellent stability to many chemical classes such as water, salts, organic acids, organic solvents, dry cleaning solvents, oxidizing agents (bleaches), reducing agents, gases and fuels. Cotton has acceptable resistance but can be disintegrated by hot dilute acids or cold concentrated acids. Cotton is unaffected by cold weak acids. Cotton fibers are resistant to some of the secondary threats such as chemicals, heat, cold or other physical hazards and should be definitely considered when tradeoffs in protection are needed.

8. Finite Element Analysis and Evaluation of Fabric Damping Properties

Knowledge of the effects of density, stiffness, and damping on the fabric's dynamics was desired. Of particular concern was the effect of these parameters on the buffeting characteristics of the fabric under a wind load. Buffeting or flutter of a fabric often directly leads to failure due to high velocity 'whipping' conditions present at free boundaries of the fabric, e.g. a sailboat's sails during high winds. While experimentation would reveal some of these effects due to parameter variation, an accurate model of this dynamic interaction would be more beneficial. First, the model would allow for an infinite number of parameter selections. Second, mathematical optimization of the fabric model would be possible. And finally, time, effort, and cost could all be reduced by the simulation of countless experiments with actual experimentation only reserved for confirmation of simulation results.

A problem this complex immediately ruled out any closed form solutions for the fabric model, hence numerical simulation of the experimental Nitinol fabric buffeting under a wind load was investigated. A finite element approach was determined to be the only feasible method of attacking such a problem for two reasons:
1) Two different highly nonlinear dynamic phenomena (turbulent airflow and a damped string or fabric vibrating with large deformations) must interact to produce a solution.
2) The boundary value nature of the problem (based on partial differential equations) dictates a finite element approach to numerical estimation.

The methodology for generating and simulating the model was as follows:

1) Generate a simple one-dimensional finite element model of a fabric (a string essentially) and demonstrate dynamic excitation with external lateral force input. Boundary conditions will be fixed-free. Large deflections will be allowed but not large strains.

2) Increase internal damping to demonstrate attenuation in response.

3) Surround the string model with a two-dimensional 'wind tunnel' meshed for fluid dynamics. A constant-velocity air front will be input from the fixed end of the string in the direction of the free end of the string. Hence the fluids mesh should be coarse toward the fixed end of the string and finer toward the free end where complex fluid effects will occur. Run a dynamic simulation and adjust velocity field until fluttering occurs without damping. (Due to symmetry a slight perturbation force might need to be added to start the string moving laterally).

4) With the same velocity field, run model again increasing damping to stop fluttering effect.

5) Also demonstrate effects of manipulating the density and stiffness of the string.

Unfortunately, at this time it appears this problem is too complex for even state-of-the-art finite element analysis software, e.g. ANSYS. This is primarily due to the fact that computational fluid dynamics (CFD) software is written in stand-alone packages because of its complexity, not allowing for interaction with other finite element packages, such as structural in this case. Additionally, even if finite element software were available that modeled fluid/structural

interactions the computational time needed to solve such a complex problem might make numerical simulation infeasible. For CFD problems, each time step must be solved iteratively; the complexity of such problems thus increases dramatically for turbulent flow problems. If a structure were allowed to flutter in the presence of turbulent flow, computation at each time step might grow to unreasonable proportions.

Experimentation must be employed to determine the effects of damping, stiffness, and density variations on the dynamics of the Nitinol test fabric under a wind load. A proposed testbed is depicted in Figure 30.

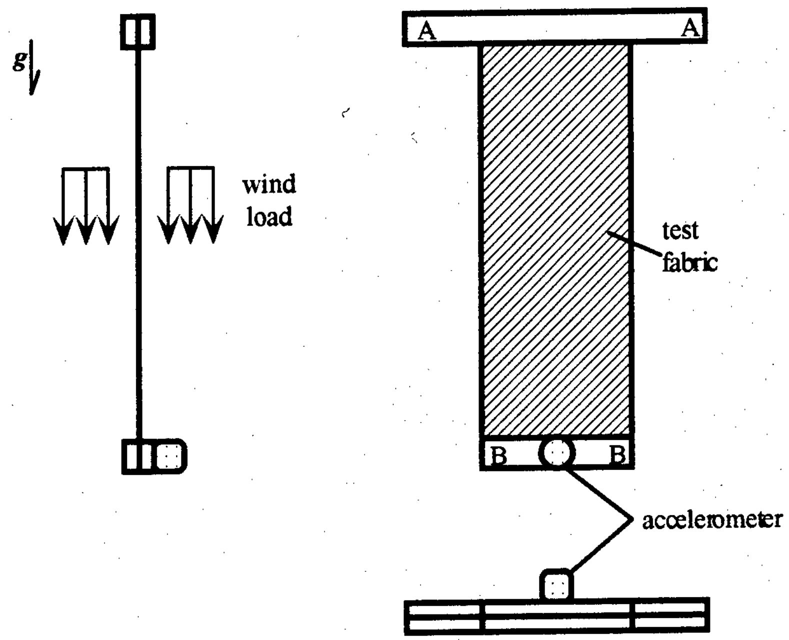


Figure 30. Side, front, and top views of experimental setup for testing the damping characteristics of Nitinol fabric

The rig is composed of a pre-specified size of fabric sample both ends of which are sandwiched between lightweight, stiff plates (such as a graphite composite). One set of plates are affixed to the wind tunnel chamber at points designated by 'A'. This mounting configuration allows the wind load to travel across the sample virtually unencumbered by the fixed boundary condition. The plates located at the free end of the sample serve two purposes: 1) they simplify mounting of the accelerometer(s) and 2) they limit end motion to primarily lateral translation and torsional rotation (two degrees of freedom). By mounting the accelerometer as shown in Figure 14, lateral translation end effects can be measured with relative insensitivity to rotational and other end effects since accelerometers are mainly sensitive to their mounting axes. However, by mounting two accelerometers at points designated by 'B' both torsional and translational responses can be measured by simply subtracting or adding the accelerometer signals, respectively.

9. Conclusions

The Phase I project was very successful in demonstrating the feasibility of using a superelastic shape memory alloy called **Nitinol** to improve cut, tear, and puncture resistance of fabric similar to the military BDU rip-stop fabric. The Nitinol reinforcement increased cut-resistance by 20 times and tear resistance by 2.5 times the standard BDU rip-stop fabric values (Section 2). While the puncture resistance was not directly measured, a relative strength in puncture is often calculated by taking a mean between the cutting and tearing (or tensile) response of a material. In this fashion, DSM-SAE engineers calculate that the puncture resistance is roughly 5 to 10 times that of standard BDU fabric using a blunt edge or knife-edge dart. Using a pointed tip dart like an ice pick, the Nitinol-reinforced fabric might increase puncture resistance by 50 to 100%.

The Phase I effort has positively demonstrated the feasibility of gaining improved protection in textiles without sacrificing fabric flexibility. Since the purpose of the Phase I effort was to demonstrate feasibility, DSM-SAE feels that the Phase I results have been very successful. The following statements summarize the findings of the Phase I study.

1. <u>Cotton/Nylon and Cotton/Polyester Plain Weave Fabrics Were Fabricated In Small Lots with Excellent Quality.</u> Various reinforced and plain fabrics were made to demonstrate enhanced mechanical performance. (Section 6)

2. <u>Nitinol Reinforcement Greatly Increases Cut Resistance.</u> Several levels of Nitinol reinforcement were added to the cotton/nylon and cotton/poly base fabrics and tested in cut resistance. The premium fabric, cotton/nylon twill with 20 Nitinol 0.005" diameter fiber per inch, exhibited 20 times the cut resistance of current BDU fabrics while maintaining a similar density. Lesser yet still significant levels of cut resistance were obtained with 5 and 10 Nitinol fibers per inch. (Section 2)

3. <u>Nitinol Reinforcement Can Increase Tear Resistance.</u> Due to the parallel nature of the load bearing Nitinol fibers, excellent resistance to tear propagation was achieved in Nitinol-reinforced fabric. The addition of the Nitinol 0.005" to the cotton/polyester-based fabric demonstrated better results than cotton/nylon reinforced fabrics. Tongue Tear Test comparative results showed an increase in tear resistance with Nitinol reinforcement to over two times the toughness of plain fabric. (Section 2)

4. <u>Nitinol Reinforcement Does Not Significantly Alter Fabric's Flexibility or Comfort.</u> The force-displacement tensile curves from the Modified Grab Test results show that the addition of Nitinol to the fabric doesn't significantly alter the stiffness or flexibility level. The tensile load versus extension data was converted to stiffness values for the fabric. The stiffness of the cotton/poly with 10 Nitinol/inch at 0.005" diameter increased by less than 10% from the plain fabric. (Section 2)

5. <u>Nitinol Reinforcement Can Increase Breaking Strength.</u> The cotton/poly fabrics experienced a 50 to 60 percent increase in breaking strength over the plain fabric with the addition of 5 and 10 Nitinol fibers per inch. (Section 2)

6. Nitinol Reinforcement Can Increase Puncture Resistance. Since estimates of the puncture resistance can be made from the tear and cut resistance, Nitinol reinforcement may improve puncture resistance by anywhere from 2 to 10 times. This topic will be covered in Phase II.

7. Nitinol Does not Significantly Alter Fabric Areal Weight. Calculations of areal density of cotton/nylon and cotton/polyester Nitinol-reinforced fabrics do not show significant difference between the cotton/nylon and cotton/polyester plain fabrics. (Section 2)

8. The Nitinol Reinforcement Adds More Than Mechanical Cut-Tear-Puncture Support. In addition to the mechanical support, Nitinol also increases secondary type threat resistance. Electrostatic discharge protection, abrasion resistance, and chemical resistance are some of the benefits that Nitinol-SMA gives to the Uniform fabric. (Section 7)

9. Nitinol Reinforcement Acts As an Anti-Static Barrier. During conversion of fiber to fabric, the large fiber surface areas are conducive to generating and holding electrostatic charges. These charges develop as a result of fiber to fiber, fiber to machinery, or fiber to air friction. The nylon fibers have the lowest moisture regain and are most likely to develop static charges. Cotton can absorb water and hence can dissipate charges more easily. Nitinol provides an electrical conduit in the uniform that minimizes shock and static discharge.

10. Nitinol's Shape Memory Response Enables Instant Recovery to Original Shape. Fabric does not kink unless subjected to very severe loads. Wrinkles cannot develop because the shape memory effect returns the Nitinol reinforcement to original shape. Fabric remains in a looser condition than standard fabric does because it does not bind. Superelastic Nitinol aids in preserving uniform shape while simultaneously maintaining high strength and comfort. (Section 1)

11. By Optimizing the Design of Nitinol-Reinforced Fabric, Its Performance Can Be Improved. Several prototype protective Nitinol-reinforced fabrics were designed and produced. Cotton/Nylon bi-directional Nitinol-reinforced fabric exhibited much better performance in cut and tear resistance than the other prototype fabrics for various reasons. It is apparent that the construction of the Nitinol-reinforced fabric can be modified and optimized in order to obtain even better protective performance.

Phase II Directions

During the Phase II program, DSM proposes to develop composite textile fabrics (host fabric with one or more reinforcements) to provide a uniform fabric system that exceeds the needs of the 21st Century Soldier. Nitinol-reinforced fabric will be a primary focus but the study will not stay with just Nitinol. The basic principal of Nitinol-reinforced fabric composite is to combine the singular properties of more than one substrate and to create a single structure that performs much better than any individual component. Kevlar® or other advanced fibers in different forms may be one of the candidates as reinforcement to the protective fabric. Other metallic and active components will be investigated in the Phase II program.

This document reports research undertaken at the U.S. Army Soldier and Biological Chemical Command, Soldier Systems Center, and has been assigned No. NATICK/TR-99/040 in a series of reports approved for publication.

10. References

Many general texts on weaving and textile technology and Nitinol-SMA response were addressed for this project. The references of a few particular texts are given here for clarity.

Kaswell E.R., "Wellington Sears Handbook of Industrial Textiles", Wellington Sears Company Inc., 1963

Kaswell E.R., "Textile Fibers, Yarns and Fabrics", Reinhold Publishing Corporation, 1953

Vigo T.L., "High-Tech Fibrous Materials", American Chemical Society, 1991

Warner S.B., "Fiber Science", Prentice Hall, 1995

Brown W.E., "Testing of polymers", John Wiley&Sons Inc., 1969

Hollies N.R., Goldman R.F., "Clothing Comfort", Ann Arbor Science, 1977

Lewin M., Preston J., "High Technology Fibers", Marcel Deccer Inc., 1989

Goswami B.C., Martindale J.G., Scardino F.L., "Textile Yarns", John Wiley&Sons Inc., 1977

Held S.E., "Weaving", Holt, Rinhart and Winstone Inc., 1973

Annual Book of ASTM Standards, "Standard Test Method for Tearing Strength of Fabrics by the Tongue Procedure", 1996

Annual Book of ASTM Standards, "Standard Test Method for Measuring Cut-Resistance of Materials Used in Protective Clothing", 1996

Annual Book of ASTM Standards, "Standard Test Method for Breaking Force and Elongation of Textile Fabrics (Grab Test)", 1996

Zho G., Goldsmith W., Dharan C.K., "Penetration of Laminated Kevlar® by Projectiles-I. Experimental Investigation", J. Solid Structures, 1992

Mallick P.K., Broutman L.J., " Static and Impact Properties of Laminated Hybrid Composites", Journal of Testing and Evaluation, 1977

Jang B.Z., Chen L.C., Hwang L.R., Hawkes J.E., Zee R.H., " The response of Fibrous Composite to impact Loading", Polymer Composites, 1990

Zee R.H., Hsien C.Y., "Energy Loss Partitioning During Ballistic Impact of Polymer Composites", Polymer Composites, 1993